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PERFORMANCE OF HYBRID PHOTOVOLTAIC COLLECTOR

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ANNEX 1

Renewable Energies

The global energy markets, are seeking to reduce greenhouse emissions. To this requires the combined use of energy renewable and their developments.

If we are responsible, if we care about the future of our planet in our children and their descendants, we should start thinking on how to squeeze every watt of power in any system producer or consumer of energy, improving efficiency of themselves and taking a responsible approach to consumption.

One solution is produce renewable energy.

Renewable energy is energy which comes from natural resources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable (naturally replenished). Renewable energy could solve many environmental problems like climate change, radioactive waste, acid rain and air pollution. Renewable energy could cover part of electricity consumption and reduce carbon dioxide emissions. In 2006, about 18% of global final energy consumption came from renewable, with 13% coming from traditional biomass, which is mainly used for heating, and 3% from hydroelectricity. New renewable (small hydro, modern biomass, wind, solar, geothermal, and befouls) accounted for another 2.4% and are growing very rapidly. The share of renewable in electricity generation is around 18%, with 15% of global electricity coming from hydroelectricity and 3.4% from new renewable.

While most renewable energy projects and production is large-scale, renewable technologies are also suited to small off-grid applications, sometimes in rural and remote areas, where energy is often crucial in human development. Kenya has the world's highest household solar ownership rate with roughly 30,000 small (20–100 watt) solar power systems sold per year.

Some renewable energy technologies are criticized for being intermittent or unsightly, yet the renewable energy market continues to grow. Climate change concerns, coupled with high oil prices, peak oil, and increasing government support, are driving increasing renewable energy legislation, incentives and commercialization. New government spending, regulation and policies helped the industry weather the 2009 economic crisis better than many other

Us in this project we are going to work about renewable energy, solar energy.

The solar energy received by our planet is the result of nuclear fusion process that takes place inside the sun. This solar radiation can be converted directly into electricity (solar electric) or heat (solar thermal). The heat, in turn, can be used to produce steam and generate electricity. Despite numerous efforts by the development of these technologies,

today there are still no high efficiency solutions that make it profitable itself to this technology.

Electric solar power:

The sun's energy is converted into electricity through photovoltaic cells, exploiting the properties of semiconductor materials. The base material for the manufacture of most photovoltaic cells is silicon. The conversion efficiency of these systems is about 15%. Even so, one square meter can provide sufficient power to operate a television medium. In order to provide electricity at night, photovoltaic cells require batteries that hold electricity generated during the day.
At present, photovoltaic systems are being developed directly connected to the mains, thus avoiding the use of batteries, so the energy generated is used immediately.

Thermal solar power:

Solar thermal systems can be classified into levels or concentration or focus. Flat solar systems are devices that heat up when exposed to solar radiation and transmit the heat to a fluid (water, for example). With the flat solar collector fluid can be heated to temperatures up to 200 º C but, in general, is used to heat to 75 º C. Concentrating solar systems are those that work by focusing sunlight on a specific area at a point or along a line. In some solar thermal power plants concentrate sunlight using mirrors, and using different technologies provide heat to medium or high temperature (in special cases, even thousands of degrees). That heat is used to generate electricity, just as in a thermal power plant. The solar heat collected during the day can be stored, so that at night or when overcast can also be generating electricity. This set of procedures or devices requires monitoring mechanisms, as the line of incidence of the sun varies during the day and during the year.

1. INTRODUCTION

Aim of the present project is the study of the performance of a combined photovoltaic-thermal plant, called also Hybrid system, located in south Italy, evaluating the efficiency of the photovoltaic and thermal systems and the advantage respect to the two single plants (photovoltaic and thermal). This research project has two objectives fundamentals of efficiency improvement energy from solar photovoltaic panels. On the one hand increase photovoltaic efficiency at the same time and same space get sanitary water.
Until now we knew two types of solar panels for harnessing solar energy, photovoltaic modules to generate electricity and thermal collectors to heat water. Both systems are completely different and independent. It is a fact that solar panels are enemies of the heat.
With the Hybrid Solar Panel, the existing heat in photovoltaic cells, which was a problem, is utilized and transferred through a heated fluid to a solar storage tank to heat water. Later I explain how works these panels.

Are all aware of the close relationship between the temperature and any system based on electricity, but does it really give you the importance? The high voltage transformers listed in your plate features that reduce the percentage of power that has a flat to after a certain temperature, the lower their electric motors efficiency when heated, electricity storage batteries photovoltaic cells, the alternators large plants producing electricity, all you have for electricity is subject to the negative effects of temperature increase. Loss in percentage value power of a power system is something substantial, but if adopt a broader view and see it globally, we sense the loss of millions of megawatts for purposes of temperature. As mentioned above, is something that physics knows, but in times of energy abundance, is neglected. We entered new times in which the energy problem will worsen.

1.1 The problem

The performance of the photovoltaic cells that are commercialized at present is understood between 15 % and 25 %, that is to say, that only a small part of the light energy takes advantage really in the shape of electric power. This performance is minor high is the temperature.

The increase of temperature in the cells supposes an increase in the current, but at the same time a very much major decrease, in proportion, of the tension. The global effect is that the power of the panel diminishes on having increased the temperature of work of the same one. A radiation of 1.000 W/m² is capable of warming a panel at least 30 degrees over the temperature of the surrounding air, which reduces the tension in 2 mV/(cell*degree) * 36 cells * 30 degrees = 2,16 Volts and therefore the power in 15 %.

On the other hand, nowadays to install photovoltaic and thermal solar power, it needs two completely independent facilities in the place of captation that habitually will be in the cover of the buildings; this implies having to have more surface to realize both facilities.

The environmental and visual impact, though small, also it is an information to bearing in mind, since if we see an isolated installation, it(he) is not significant, but if we see it from a more widespread point of view, might remember(remind) the forests of antennas that we saw in the roofs not a lot of time ago.

The present project tries to contribute some viable solution to the raised problems.

1.2 Justification

After having seen the direct relation between temperature and energetic efficiency of the solar panels has been investigated in Internet, books, specializing magazines not finding any technical solution that settles the problem of the temperature in the photovoltaic panels, that on the other hand it is inherent in the own solar power.
Though it is true that in the photovoltaic facilities is advisable to place the panels in drafty well places, to relieve the negative effects of the temperature on the photovoltaic cells, also it is true that is failing to take advantage of the energy in the shape of heat that exists in the same ones.

On the other hand the idea of integrating (repaying) photovoltaic and thermal solar power in the same panel is a new concept, and that is worth investigating, since it would carry the following advantages:

- Significant reduction of necessary space to install both systems (thermal and photovoltaic systems).
- Fewer residues reached the end of the useful life of the installation.
- I increase of at least 15 % in the production of electricity (photovoltaic power).
- Water warming for sanitary uses, heating, swimming pools, etc.
- Prolongation of the useful life of the modules, on having reduced his temperature of work.
- Reduction of the solar reflected radiation.

- Cost reduction for the production and installation of both systems.
- Fewer iron-works and points of anchorage.
- Less environmental impact.
- Better architectural integration.
- In solar gardens, more performance and reduction of the time of amortization. In solar gardens is where the Solar Hybrid Panel is used as a Photovoltaic module with refrigeration.

1.3 Viability

Since the energy efficiency of solar panels PV may be considered by 19% on average. This project will create very feasible to develop such technology, since 19% of existing efficiency must be combined at least a 15% gain in electricity production is should be mainly due to reduced degradation by temperature effects on cells.
In all it also should be added at least 30% energy captured in a heat, bringing the obtained result is very higher than currently achieved.

Production costs would be lower because in the same component would be located all collectors.
At the time of making the facilities would be needed less supports and anchorage points.

2. THEORETICAL FRAMEWORK

2.1 Semiconductors

A semiconductor is a component that is not directly a current driver, but it is an insulator. In a conductor current is due to movement of charge negative (electrons). In semiconductors are produced currents produced by both the movement of electrons as of positive charges (holes). Semiconductors are those elements belonging to group IV of the Periodic Table (Silicon Germanium, etc.).. Generally these atoms was introduced other elements, known impurities, so that the current is due primarily to electrons or holes, depending on the impurity introduced.

2.2 Effect of temperature on materials

The resistance of a metallic conductor increases with increasing temperature. This increase depends on the elevation of the temperature and thermal resistivity coefficient alpha (α), which is defined as the change in resistivity per degree centigrade variation. Semiconductors have a negative coefficient of temperature, while many metals become superconductors few degrees above absolute zero.
The working temperature (Tt) reaching a photovoltaic panel obeys a linear relationship given by the expression:

$$Tt=Ta+K.R$$

- Tt: work temperature.
- Ta: maximum atmosphere temperature.
- R: solar radiation in mW/cm² (varies between 80 and 100 mW/cm²).
- K: coefficient varies between 0,2 y 0,4 ºC.cm²/mW depending

the average wind speed. When it is very low, or nonexistent, the panel cooling is poor or zero and taking K values close or equal to the maximum (0.4). If the speed of wind produces effective cooling of the panel, the values of K will the minimum (0.2).

K.R: Represents the temperature increase that the panel gets on the maximum atmosphere temperature.

To calculate the output power to the working temperature (Pt) that reaches a photovoltaic panel, the first step is to calculate the working temperature and then determining the increase in
temperature as compared to the test (25 º C). The approximate expression for the calculation is:

Pt= Pp* ζ*Dt

- Pt: Output to the working temperature.
- Pp: Peak power of the panel (25 ºC).
- ζ: coefficient of degradation (0,6 % / ºC).
- Dt: Temperature increase on the 25 ºC (Tt - 25ºC).

The technical staff of HOME POWER magazine has conducted a series of assessments, using panels of cells different types of work at temperatures not below 50 ° C.
The results of these tests have been published in three of his numbers: 24 (pp. 26-30) and 33 (pp. 17-20) and 49 (pp.28-33) .The latest assessment is the most interesting for two reasons:
was carried out after a long use of the panels tested and the working temperature is that of summer. They evaluated nine panels with three different types of cells: crystalline, polycrystalline and amorphous. The results show that most of the panels, regardless of the cell, provide a degradation rate of between 0.7 to 0.86%.

2.3 Solar cell

A solar cell is a device that converts the energy of sunlight directly into electricity by the photovoltaic effect. Sometimes the term solar cell is reserved for devices intended specifically to capture energy from sunlight such as solar panels and solar cells, while the term photovoltaic cell is used when the light source is unspecified. Assemblies of cells are used to make solar panels, solar modules, or photovoltaic arrays. Photovoltaics is the field of technology and research related to the application of solar cells in producing electricity for practical use. The energy generated this way is an example of solar energy (also known as solar power).

2.3.1 Introduction

Solar electricity or photovoltaic has shown since 1970s that the human race can get a substantial portion of its electrical power without burning fossil fuels (coal, oil or natural gas) or creating nuclear fission reactions. The Sun provides us with a staggering amount of free, environmentally friendly, quiet and reliable energy supply. Earth's ultimate recoverable resource of oil, estimated at 3 trillion barrels, contains 1.7x1022 joules of energy, which the Sun delivers to our planet in 1.5 days. Since 120,000 TW of solar radiation strikes on the surface of the Earth, 10% efficient solar conversion systems covering 0.16% of the land would produce 20 TW of power, nearly twice the annual global energy consumption.

Photovoltaic can generate electricity for a wide range of applications, scales, and climates; it is a cost-effective way to provide power to remote areas and for space applications. Table 1 lists some of the technical, economical and infrastructural features of photovoltaic, showing that photovoltaic helps us avoid most of the threats associated with our present techniques of electricity production and also has many other benefits.

Advantages	Disadvantages
Fuel source is vast and essentially infinite	Fuel source is diffuse (sunlight is a relatively low density energy)
No emissions, no combustion or radioactive fuel for disposal (does not contribute perceptibly to global climate change or pollution)	High installation costs
Low operating costs (no fuel)	Poorer reliability of auxiliary (balance of system)
No moving parts (no wear)	elements including storage
Ambient temperature operation (no high temperature corrosion or safety issues)	Lack of widespread commercially available system
High reliability in modules (>20 years)	integration and installation so far
Modular (small or large increments)	
Quick installation	Lack of economical efficient energy storage
Can be integrated into new or existing building structures	
Can be installed at nearly any point-of-use	

Daily output peak may match local demand High public acceptance Excellent safety record	

Table 2.1

The enormous gap between the potential of solar energy and our currently slight use of it is due to the modest energy density of the radiation, low conversion efficiencies of photovoltaic, and cost of materials currently required. The cost effective raising of conversion efficiency is primarily a scientific challenge: breakthroughs in fundamental understanding enable the development of materials and methods leading to the photovoltaic market progress.

A history of photovoltaic goes back to 1839, when Edmund Becquerel observed a photovoltaic effect in liquid electrolytes. However it was not until 1954 that the first solar cell was developed at Bell Laboratories. Modern research in the area of photovoltaic technologies has lead to creation of a huge spectrum of solar cells, which are commonly classified as three generations, which differ from one another based on the material and the processing technology used to fabricate the solar cells. The material used to make the solar cell determines the basic properties of the solar cell, including the typical range of efficiencies .The first generation of solar cells, also known as silicon wafer-based photovoltaic, is the dominant technology for terrestrial applications today, accounting for more than 85% of the solar cell market. Single-crystalline and multi-crystalline wafers, used in commercial production, allow power conversion efficiencies up to 25%, although the fabrication technologies at present limit them to about 15 to 20%. The second generation of photovoltaic materials is based on the use of thin-film deposits of semiconductors, such as amorphous silicon, cadmium telluride, copper indium gallium dieseline or copper indium sulfide. The efficiencies of thin film solar cells tend to be lower compared to conventional solar cells, around 6% to 10%, but manufacturing costs are also lower, so that a price in terms of $/watt of electrical output can be reduced. Besides, decreased mass allows fitting panels on light materials or flexible materials, even textiles.

The third generation of photovoltaic cells is a research goal: a dramatic increase in efficiency that maintains the cost advantage of second-generation materials. The approaches include desensitized nanocrystalline or Gratzel solar cells, organic polymer-based photovoltaic, tandem (or multi-junction) solar cells, hot carrier solar cells, multi-band and thermo photovoltaic solar cells.

This project is focused on multi-junction solar cells that use a combination of semiconductor materials to more efficiently capture a larger range of photon energies.

Depending on the particular technology, present-day multi-junction solar cells are capable of generating approximately twice as much power under the same conditions as traditional solar cells made of silicon.

Multi-junction solar cells have a highest theoretical limit of efficiency conversion as compared to other photovoltaic technologies. A present-day record efficiency of 40.7% was achieved exactly with a multi-junction solar cell by Boeing Spectrolab Inc. in December 2006. At first, fundamentals of photovoltaic cells will be described. Then, current solar cell design and performance will be presented, and future design improvements will be.

2.3.2 Foundations of photovoltaic

The solar spectrum in outer space resembles the theoretical radiation provided by a black body of 5900 K. As the light passes through the atmosphere, some of the light is absorbed or reflected by gasses such as water vapor and the ozone. The spectrum of the sun's light that reaches Earth's upper atmosphere ranges from the ultraviolet to the near infrared radiation, with peak region (48%) from 400 to 700 nm, which is the visible diapason (Figure 2.1).

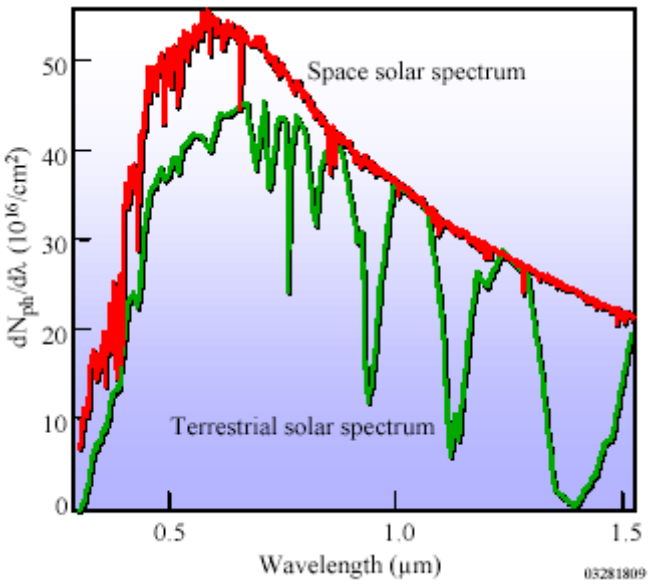


Figure 2.1 Terrestrial and space solar spectrum .

Photovoltaic cells can be defined as p-i-n photodiodes, which are operated under forward bias. They are designed to capture photons from the solar spectrum by exciting electrons across the band gap of a semiconductor, which creates electron-hole pairs that are then charge separated, typically by p-n junctions introduced by doping. The space charge at the p-n junction interface drives electrons and holes in opposite directions, creating at the external electrodes a potential difference equal to the band gap

(Figure 2.2) . A semiconductor can only convert photons with the energy of the band gap with good efficiency. Photons with lower energy are not absorbed and those with higher energy are reduced to gap energy by thermalization of the photogenerated carriers.

Behaviour of a solar cell is represented by current versus voltage curves on Figure 2.3. The point at which a curve intersects the vertical axis is known as the short circuit condition, and it defines how the cell operates if a wire is connected between its terminals, shorting it out. The current flow here is known as short-circuit current, *I sc* . For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical.

Therefore, the short-circuit current is the largest current which may be drawn from the solar cell. The point at which a curve intersects the horizontal axis is known as the open circuit condition. The open-circuit voltage, *V oc,* is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current. Voc depends on the saturation current of the solar cell and the light-generated current. Open-circuit voltage is then a measure of the amount of recombination in the device.

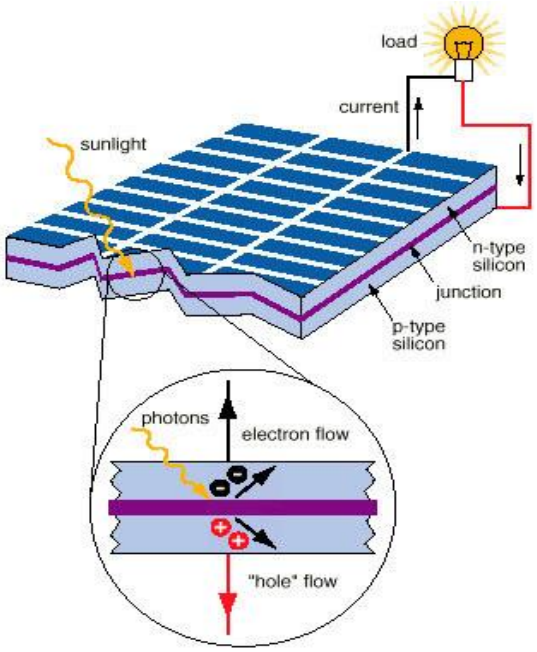


Figure 2.2 A diagram of a solar cell.

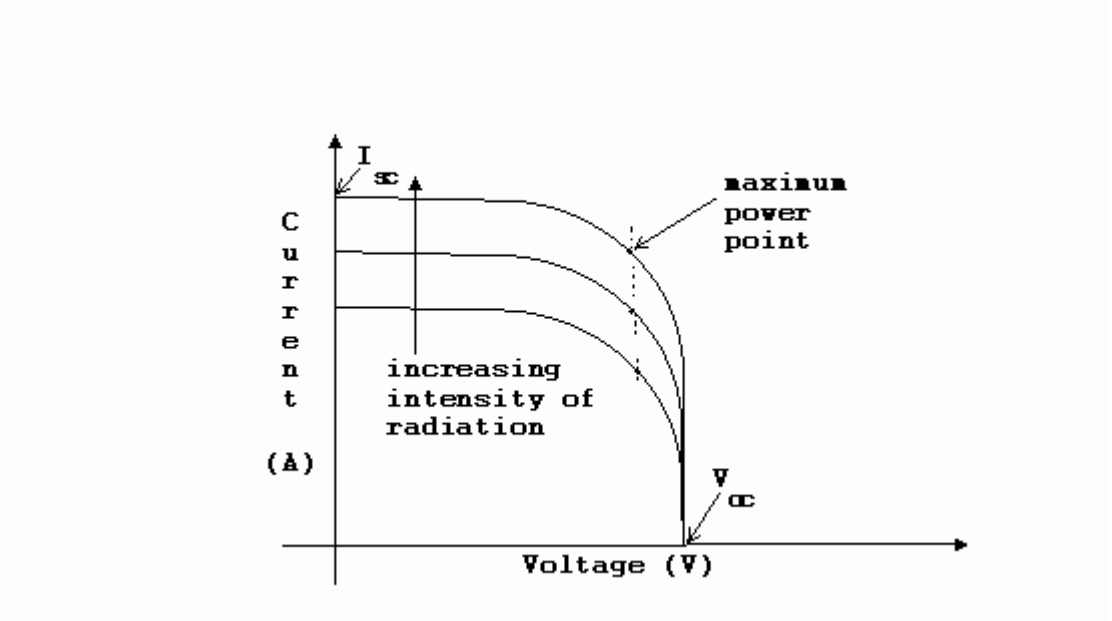


Figure 2.3 Characteristic I-V curves for a solar cell.

For each point on the graph, the voltage and current can be multiplied to calculate power. Maximum power point is the point on the I-V curve of a solar cell corresponding to the maximum output electrical power,

$$P_m\,[Watts] = V\,\max * I\,\max$$

Maximizing total power is the goal of solar cell's design. Multi-junction photovoltaic, as compared to single-junction cells, have reduced currents, because fixed total number of photons is distributed over increasing number of cell layers, so that the amount available for electron promotion in any one layer is decreased. At the same time, the electrons excited are more energetic and have a greater electric potential, so the reduction of currents is compensated for by increase in voltages, and the overall power of the cell is greater. Moreover, multi-junction design is advantageous, because resistive losses, which are proportional to the square of the current, can be significantly reduced.

Another defining term in the overall behaviour of a solar cell is the fill factor, *FF*. This is the ratio that describes how close the I-V curve of a solar cell resembles a perfect rectangle, which represents the ideal solar cell:

$$FF = Pm\ /\ (V_{oc} * I_{sc})$$

Quantum efficiency is a term intrinsic to the light absorbing material and not the cell as a whole; it refers to the percentage of absorbed photons that produce electron-hole pairs. Whereas energy conversion efficiency, is the percentage of incident electromagnetic radiation that is converted to electrical power, when a solar cell is connected to an electrical circuit. This overall efficiency depends on many factors

including the temperature, amount of incident radiation and the surface area of the solar cell.

Generally, a photovoltaic cell has a thickness that varies between 0.25 and 0.35 mm and a generally square shape, with an area approximately equal to 100 mm^2.

The materials for the manufacture of solar cells are:

- Monocrystalline Silicon: energy efficiency 15 - 17%

- Ply-crystalline Silicon: energy efficiency 12 - 14 %

- Amorphous Silicon: With lower energy efficiency of 10 %

- Other materials: gallium arsenide, copper indium dieseline, cadmium telluride.

Actually the most widely used material is silicon, monocrystalline which has benefits and length of time over any other material used for the same purpose.

2.3.3 High-efficiency cells

High-efficiency solar cells are a class of solar cell that can generate more electricity per incident solar power unit (watt/watt). Much of the industry is focused on the most cost efficient technologies in terms of cost per generated power. The two main strategies to bring down the cost of photovoltaic electricity are increasing the efficiency of the cells and decreasing their cost per unit area. However, increasing the efficiency of a solar cell without decreasing the total cost per kilowatt-hour is not more economical, since sunlight is free. Thus, whether or not "efficiency" matters depends on whether "cost" is defined as cost per unit of sunlight falling on the cell, per unit area, per unit weight of the cell, or per unit energy produced by the cell. In situations where much of the cost of a solar system scales with its area (so that one is effectively "paying" for sunlight), the challenge of increasing the photovoltaic efficiency is thus of great interest, both from the academic and economic points of view. Many groups have published papers claiming possibility of high efficiencies after conducting optical measurements under many hypothetical conditions. The efficiency should be measured under real conditions and the basic parameters that need to be evaluated are the short circuit current, open circuit voltage.

The chart at the right illustrates the best laboratory efficiencies obtained for various materials and technologies, generally this is done on very small, i.e. one square cm, cells. Commercial efficiencies are significantly lower.

a) Multiple-junction solar cells

Basic Principles of Multi-Junction Solar Cells

The highest-efficiency solar cells use multiple materials with bandgaps that span the solar spectrum. Multi-junction solar cells consist of some single-junction solar cells stacked upon each other, so that each layer going from the top to the bottom has a smaller bandgap than the previous, and so it absorbs and converts the photons that have energies greater than the bandgap of that layer and less than the bandgap of the higher layer.

Multi-junction solar cells experience a fundamental limitation relating to the availability of materials with optimal band gaps that simultaneously allow high efficiency through low defect densities. Alloys of groups III and V of the periodic table are good candidates for fabricating such multijunction cells: their band gaps span a wide spectral range, and most of the bandgaps have direct electronic structure, implying a high absorption coefficient, and their complex structures can be grown with extremely high crystalline and optoelectronic quality by high-volume growth techniques.

Multi-junction solar cells have been studied since 1960. The first multi-junction device was demonstrated in early 1980s, and it converted 16% of the solar energy into electricity. In 1994, US National Renewable Energy Laboratory (NREL) broke the 30% barrier. A present-day record 40.7% efficiency was achieved with a triple-junction version of the cell . The maximum theoretical limit efficiency of multi-junction solar cells is 86.8%.

Bandgaps

In order to optimize conversion efficiency of a photovoltaic cell, the solar cell should absorb as much of the spectrum as possible, and so bandgaps should cover a wide range. Besides, bandgaps of adjacent layers should differ by as small amount as possible, because the amount of excess energy from light converted to heat is equal to the difference between the photon energy and the bandgap of the absorbing material.

Gas has nearly the optimal band gap (1.4 eV) for solar energy conversion in a conventional solar cell design, which is inherently limited to efficiencies of about 25% or less at one-sun concentration.

Triple-junction solar cells currently in production are made of GaInP (1.9 eV), GaAs (1.4 eV), and Ge (0.7 eV); advanced multi-junction solar cell concepts foresee use of AlGaInP (2.2 eV), AlGaAs (1.6 eV), GaInP (1.7 eV), GaInAs (1.2 eV), GaInNAs (1.0-1.1 eV) [26]. For example, Spectrolab's record-breaking cell used Ga0.5In0.5P (or GaInP2) with bandgap energy of 1.85 eV and the lattice constant of 5.65 angstroms. Less gallium and more indium would be used in the compound, if a lower bandgap material were desired, up to the resulting InP with bandgap energy of 1.3 eV and the lattice constant of 5.88 angstroms. However, such an adjustment in bandgaps should be made in conjunction with lattice-constant constraints.

b) Thin-film solar cells

Introduction to How Thin-film Solar Cells Work

The solar panel is an enduring icon of the quest for renewable energy. You'll see the black-paned rectangles on the rooftops of houses or assembled into arrays across fields and prairies. But the panel as we have come to know it -- 5.5 feet by 2.75 feet by 2 inches (1.7 m by 0.8 m by 5 cm) -- may be history. That's because a new type of technology stands ready to take its rightful place next to traditional silicon wafer-based panels as an efficient, cost-effective way to convert sunlight into electricity. The technology is the **thin-film photovoltaic (PV) cell**, which, by 2010, will be producing 3,700 megawatts of electricity worldwide [source: National Renewable Energy Laboratory].

What is a Thin-film Solar Cell?

If you've used a solar-powered calculator, you've seen a solar cell based on thin-film technology. Clearly, the small cell in a calculator is not big and bulky. Most are about an inch (2.5 cm) long, a quarter-inch (0.6 cm) wide and wafer-thin. The thinness of the cell is the defining characteristic of the technology. Unlike silicon-wafer cells, which have light-absorbing layers that are traditionally 350 microns thick, thin-film solar cells have light-absorbing layers that are just one micron thick. A micron, for reference, is one-millionth of a meter (1/1,000,000 m or 1 µm).

Thin-film solar cell manufacturers begin building their solar cells by depositing several layers of a light-absorbing material, a semiconductor onto a substrate -- coated glass, metal or plastic. The materials used as semiconductors don't have to be thick because they absorb energy from the sun very efficiently. As a result, thin-film solar cells are lightweight, durable and easy to use.

There are three main types of thin-film solar cells, depending on the type of semiconductor used: amorphous silicon (a-Si), cadmium telluride (CdTe) and copper

indium gallium deselenide (CIGS). Amorphous silicon is basically a trimmed-down version of the traditional silicon-wafer cell. As such, a-Si is well understood and is commonly used in solar-powered electronics. It does, however, have some drawbacks.

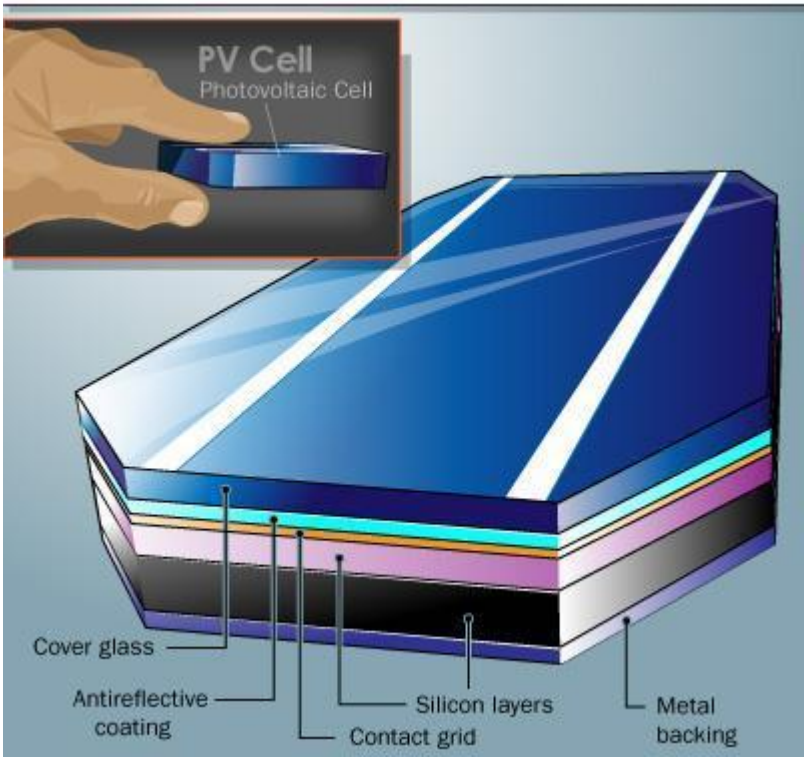


Figure 2.4 The layers of a photovoltaic (PV) solar cell

A copper indium gallium deselenide solar cell using glass

One of the biggest problems with a-Si solar cells is the material used for its semiconductor. Silicon is not always easy to find on the market, where demand often exceeds supply. But the a-Si cells themselves are not particularly efficient. They suffer significant degradation in power output when they're exposed to the sun. Thinner a-Si cells overcome this problem, but thinner layers also absorb sunlight less efficiently. Taken together, these qualities make a-Si cells great for smaller-scale applications, such as calculators, but less than ideal for larger-scale applications, such as solar-powered buildings.

Promising advances in non-silicon thin-film PV technologies are beginning to overcome the issues associated with amorphous silicon. On the next page, we'll take a look at CdTe and CIGS thin-film solar cells to see how they compare.

Structure of Thin-film Solar Cells

Because structure and function are so closely linked with solar cells, let's take a moment to review how they work. The basic science behind thin-film solar cells is the same as traditional silicon-wafer cells.

Photovoltaic cells rely on substances known as semiconductors. Semiconductors are insulators in their pure form, but are able to conduct electricity when heated or combined with other materials. A semiconductor mixed, or "doped," with phosphorous develops an excess of free electrons. This is known as an **n-type semiconductor**. A semiconductor doped with other materials, such as boron, develops an excess of "holes," spaces that accept electrons. This is known as a **p-type semiconductor**.

A PV cell joins n-type and p-type materials, with a layer in between known as a **junction**. Even in the absence of light, a small number of electrons move across the junction from the n-type to the p-type semiconductor, producing a small voltage. In the presence of light, photons dislodge a large number of electrons, which flow across the junction to create a current. This current can be used to power electrical devices, from light bulbs to cell phone chargers.

Traditional solar cells use silicon in the n-type and p-type layers. The newest generation of thin-film solar cells uses thin layers of either cadmium telluride (CdTe) or copper indium gallium deselenide (CIGS) instead. One company, Nanosolar, based in San Jose, Calif., has developed a way to make the CIGS material as an ink containing nanoparticles. A nanoparticle is a particle with at least one dimension less than 100 nanometers (one-billionth of a meter, or 1/1,000,000,000 m). Existing as nanoparticles, the four elements self-assemble in a uniform distribution, ensuring that the atomic ratio of the elements is always correct.

The layers that make up the two non-silicon thin film solar cells are shown below. Notice that there are two basic configurations of the CIGS solar cell. The CIGS-on-glass cell requires a layer of molybdenum to create an effective electrode. This extra layer isn't necessary in the CIGS-on-foil cell because the metal foil acts as the electrode. A layer of zinc oxide (ZnO) plays the role of the other electrode in the CIGS cell. Sandwiched in between are two more layers -- the semiconductor material and cadmium sulfide (CdS). These two layers act as the n-type and p-type materials, which are necessary to create a current of electrons.

A cadmium telluride (CdTe) solar cell

But how does the efficiency of thin-film solar cells compare to traditional cells? The theoretical maximum for silicon-wafer cells is about 50 percent efficiency, meaning that half of the energy striking the cell gets converted into electricity. In reality, silicon-wafer cells achieve, on average, 15 to 25 percent efficiency. Thin-film solar cells are

finally becoming competitive. The efficiency of CdTe solar cells has reached just more than 15 percent, and CIGS solar cells have reached 20 percent efficiency.

There are health concerns with the use of cadmium in thin-film solar cells. Cadmium is a highly toxic substance that, like mercury, can accumulate in food chains. This is a blemish on any technology that fancies itself part of the green revolution. The National Renewable Energy Laboratory and several other agencies and companies are currently investigating cadmium-free thin-film solar cells. Many of these technologies are proving themselves to be just as efficient as those that require cadmium.

So how are these next-generation solar cells manufactured? Read on and find out.

Production of Thin-film Solar Cells

Cost has been the biggest barrier to widespread adoption of solar technology. Traditional silicon-wafer solar panels require a complex, time-consuming manufacturing process that drives up the per-watt cost of electricity. Non-silicon thin-film solar cells are much easier to manufacture and therefore remove these barriers.

c) Crystalline Silicon

Crystalline silicon (c-Si) photovoltaic cells deliver the highest efficiencies of any type of solar cell, with leading cells having efficiencies of over 20% in production. Today, approximately 80% of PV solar panels produced are based on c-Si technology that has shown excellent long-term reliability and performance over several decades of use. c-Si solar cells are made from silicon "wafers," which may have either single-crystalline (also called mono-crystalline) or multi-crystalline (also called poly-crystalline) molecular structures.

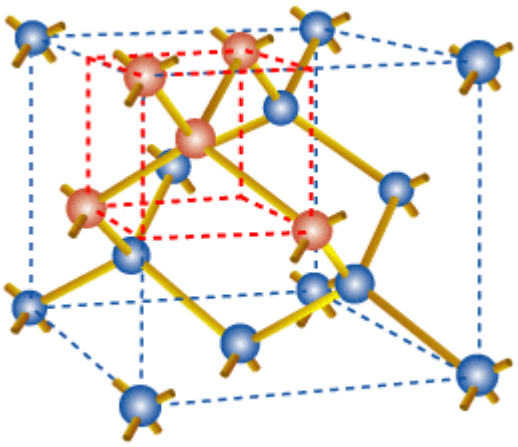


Figure 2.5 example of Crystaline Silicon structure.

Single-crystalline silicon is more efficient at electricity generation from solar panels but is more expensive than poly-crystalline manufacturing. Crystalline cells are uniformly constructed from slices of a large single crystal ingot. The orderly arrangement of atoms results in sunlight conversion efficiency.

Poly-crystalline silicon is composed of many crystals, or grains. Atomic order is disrupted at grain interfaces, making poly-crystalline silicon less efficient at converting sunlight power into electricity.

The solar cell is made by adding electrically conductive elements to the silicon wafer ("doping") and coating with thin layers of specialized materials. Because the silicon wafer is a large part of the cost, it is critical to reduce the amount of silicon by using thinner wafers to drive down cost per watt.

As the world's largest supplier of c-Si production equipment, Applied Materials offers a broad range of market-leading, best-in-class equipment for c-Si manufacturing. Our systems are used in manufacturing the world's most efficient commercially available solar cells, including by all of the top 15 wafer manufacturers and 14 of the top 15 cell manufacturers. These systems' high productivity advanced ultra-thin wafer handling and extensive automation can drive significant cost reductions, resulting in lower cost per watt.

In addition to our manufacturing systems, Applied's advanced hardware and software automation solutions are unique in the solar industry, enabling crystalline silicon manufacturing customers to improve equipment efficiency as well as increase fab throughput and yield. By preventing processing errors, reducing product variation, optimizing material movement and increasing energy conversion efficiency, these automation products can significantly enhance factory productivity.

Applied's Expert Connect, a remote access service solution, will soon be available for c-Si solar customers. This technology, which has helped semiconductor service customers reduce system downtime by over 20%, utilizes a structured escalation methodology and an extensive global knowledge database to improve system availability and speed service response.

3. THEORETICAL MODEL FOR DETERMINING THE TEMPERATURE OF THE CELL, WITHOUT REFRIGERATION

3.1 Introduction

It was investigated the possibility of developing a theoretical model (stationary) that allows a easy form to find the temperature of the used cell , in addition to outside air temperature and irradiation, the temperature of the glass cover of the module.
In analogy to the theory of solar collectors, heat conduction in a photovoltaic module can be reproduced by the following equivalent electrical circuit with resistors R1,R2 y R3 (Figure 3.1) . The difference from the solar collector consists mainly in the fact that a photovoltaic module, including the cover glass and modules, there is no cushion of air, the glass sticks to cells and any small gaps are of special make up with plastic. In this sense photovoltaic module is therefore a continuous element.

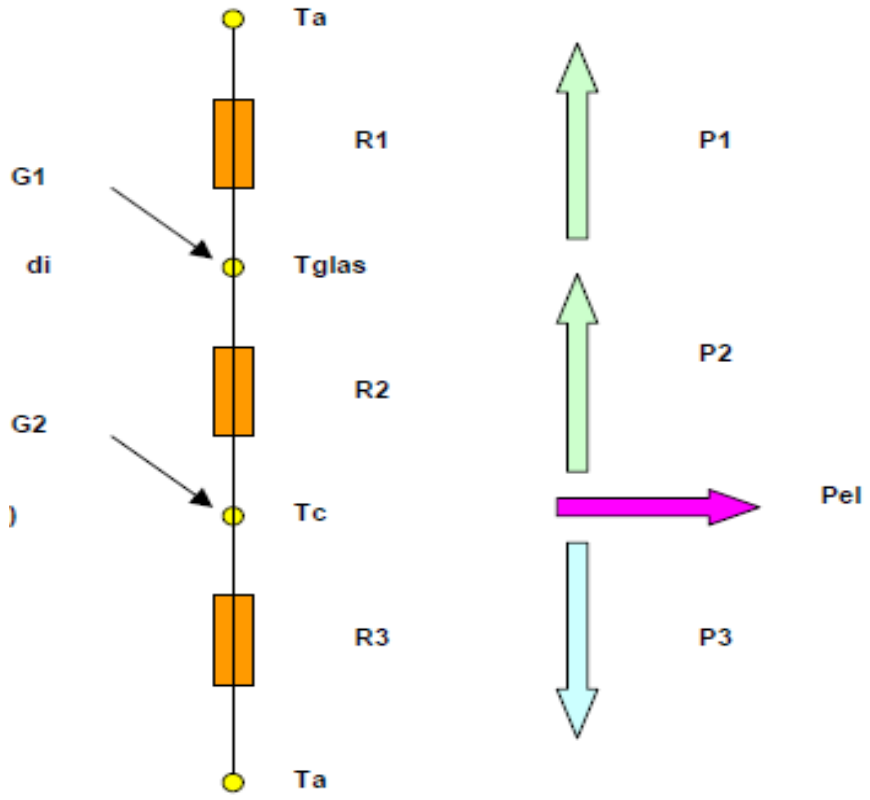


Figure 3.1 Simplified model of the equivalent electrical circuit of a PV module with glass coverage.

Legend figure 3.1.

R1 (m² °C/W) = 1/Ho where Ho = αcv,o + αirr,o. R1 R1 is the thermal resistance between the glass and the external environment, and αcv,o + αirr,o (in W/m2 ° C) the respective ratios of convection and radiation to the front of the module.

R2 (m² °C/W) = δg/λg where δg (m) is the thickness of cover glass and λg (W / m ° C) thermal conductivity of the same.

R3 (m² °C/W) = [(δp/λp**) +** 1 **/** (Hu)**],** where δp (m) is the thickness of the plastic side and rear λp (W /m ° C) thermal conductivity of the same, Hu = αcv,u+ αirr,u(W/m2 ° C) is the convection coefficient and respectively between irradiation layer covering the external environment in the back of the module.

Ta(°C) = ambient temperature.

Tglas (°C) = temperature on the surface of the glass cover (measured).

Tc (°C) = PV cell temperature.

Pel (W/ m²) = electrical power supplied by the module (here expressed in W per m2 of module), measured or calculated.

P1 (W/ m²) = thermal convection and radiation transmitted to the outside (front of module, here expressed in W for m² of module).

P2 (W/ m²) = thermal power transmitted by conduction between cells and glass (the front of the module, here expressed in W for m² of module).

P3 (W/ m²) = total thermal power transmitted between cells and the external environment in the back of the form here expressed in W for m² of module (by conduction through the plastic rear and by convection and radiation to the outside).

Gg or G (W/ m²) = instantaneous global solar radiation in W/ **m²** incident on the module (measured).

G1 (W/ m²) = instantaneous solar radiation absorbed by the cover glass, G1 = (αglas) * Gg, where (αglas) is the degree of absorption of solar radiation by the glass (average value over the entire solar spectrum).

G2 (W/ m²) = instantaneous solar radiation absorbed by the cell, G2 = (ζα) ***** Gg, where (ζ) is the degree of transmission of the glass takes into account not only of reflection, absorption is the degree of glass (α) is the absorption of form (average value over the entire solar spectrum).

The term R1 represents the resistance to thermal conductivity of heat between the glass cover and the external environment in the front of the module, R2 thermal resistance between cells and glass coverage, while the term R3 is the total thermal resistance present between the cell (through the coverage plastic) and the external environment in

the back of the module. It should be noted that the expression for R1 is simplification, since the outside air temperature differs from the temperature of the air and two elements, αcv,o + αirr,o should be considered in more detail and separately.

Solar radiation incident on the form is partly reflected on the glass cover, partly absorbed (G1, usually very little) and partly transmitted (ζ) from the same, only to be partly absorbed by the cells. The product (ζα) (it is understood by the average over the entire solar spectrum) thus represents the degree of radiation actually absorbed by solar cells, where α indicates the degree of absorption. The coefficient (ζα) (as αglas well) is dependent on several factors, such as material characteristics, the coefficients of refraction, the angle of incidence of solar radiation, etc. .. And 'to mention that for the photovoltaic cells produced (ζα) is usually not known precisely, and according to specific literature. This value can be estimated at around 0.9. In our case it was decided to consider angle of incidence of radiation, so by calculating the transmission coefficient (ζ) of glass angles for the day 18.11.99 incidence between 0 - 45 ° (with an extinction coefficient of glass K = 4 (m-1)). It was finally obtained a coefficient (ζα) between 0.83 and 0.86, assuming a rate of absorption of solar radiation cell (α) between 0.9 - 0.95, depending on the angle of incidence. The values of (ζα) thus obtained are similar to those proposed.

In principle, such as simplification, one could proceed with a constant value of (αζ) between 0.8 - 0.9, and in doing so the error in determining the temperature of the cell, seen in relation to the electrical power produced from PV, it would be minor. However, taking into account also angle of incidence of solar radiation and its direct and diffuse component, you can perform simulations that better reflect the real conditions existing in a day of sunshine any, resulting in more accurate results of Tc.

The reaction that takes place within a PV module is characterized first by an electrical process, where electrical power is delivered according to the temperature of the cell (here called by Pel, in terms of power for m² of module, W/ m²) and the other side by a thermal process, where part solar radiation absorbed G2 (and G1 by the glass) is dispersed as heat to the rear and front of the form (P1, P2 and P3, expressed in W per m² of module W/ m². Neglecting the heat capacity of the module (this aspect will return later), in a case stationary on the basis of energy conservation can be made the following expressions:

1) **A * G1 + A * P2 - A * P2 = 0**

2) **A * G2 + A * P2 - A * P3 – A * Pel = 0**

Where A = collector surface, in m^2.

The values of heat loss, P1, P2 and P3 can be determined as follows:

3) **P1 = Ufront *(Tglas – Ta) or P1 = U1 *(Tglas – Ta)**

4) **P2 = Uglas *(Tc – Tglas) or P2 = U2 *(Tc – Tglas)**

5) **P3 = Uback *(Tc – Ta) or P3 = U3 *(Tc – Ta)**

Where Ufront (U1) is the coefficient of heat transmission between the cover glass and the external environment, Uglas (U2) between the module and the cover glass and finally Uback (U3) total heat transfer coefficient between the module and the external environment for the back of the module.

6) **Pel = I_M * V_M**

$I_M = I_0 * (G2/G0) * (1 + \gamma (T_c - T_{ref}))$

$V_M = V_0 * (1 + \beta (T_c - T_{ref}))$

Where I_M , V_M and Pel are respectively the maximum current, voltage, and power of the PV system, G2 is the incoming sun radiance, G0 and Tref are respectively the design radiance and the reference temperature. γ and β are known parameters valid for the chosen PV collector and Tc is the plate temperature. Usually the power given by the collector is the maximum one Pel, due to an appropriate control system.

7) **G1 = (αglas) * G**

8) **G2 = (ζα) * G**

Where G is the sun irradiance.

These ratios are calculated on the basis of thermal resistances described in the model and have the following expression (in W/ m^2 ° C):

9) **Ufront (U1) = 1/R1 = 1/ { 1/(α;cv,o + α;irr,o)} = (α;cv,o + α;irr,o) = Ho**

10) **Uglas (U2) = 1/R2 =λg/δg**

11) **Uback (U3) = 1/R3 = 1/ { (1/(α;cv,u + α;irr,u)) + (δp/ λp)} = 1/{(1/ Hu) + (δp / λp)}**

I also need to distinguish between the front of the module (front) and Hu in the rear of form (back) since the first case the module is turned toward the sky, while the latter towards the low, the below the ground.

In order to actually use the equations (1) and / or (2) for the calculation of Tc, it is necessary to know advance ratios of convection and radiation (α; cv + α; irr) and appearing in Ufront and Uback. Actually, these factors, in addition to being constant, depends on many factors (wind, emissivity of materials, tilt module, weather, etc. ..) and are not easy to determine with precision.
Moreover, in this context, there is a multitude of formulas from the literature that are based on specific experimental data and often have important differences in the results. By contrast, the coefficient Hu appears in Uback (then a heat flow down the back of the form), presents fluctuations much less strong that I, as the latter characterizes the events of convection and irradiation of the form that looks to the sky (here play an important role sky temperature, cloud, mixed events between forced and natural convection, wind, etc.). and much more exposed to weather than the rear. Since the known temperature glass (measured), just one of the two equations for the calculation of Tc. Based on a series of inspections performed, it was found that using Eq. (2) (which appears only Uback) and assuming for a Hu average of 6 to 7 W/m2 ° C, as proposed by the SIA and most of the literature specific, you make a calculation error that is less than that using Eq. (1) where it appears Ufront.
Based on the above you can write the following expression:

$$\mathbf{A*G2 = A*(\zeta\alpha)* G = A*Uback *(Tc - Ta) + A*Uglas *(Tc - Tglas) + A*Pel}$$

Eliminating the surface to form the equation, and after a few steps of calculation is obtained for Cell temperature (Tc) the following linear expression:

$$\mathbf{Tc = [(Ta*Uback)+ (Tglas*Uglas) + ((\zeta\alpha)*G - Pel)] / [Uback / Uglas]}$$

This formula brings together all the key elements that determine the temperature of the cell, such as thermal parameters of PV, the temperature of the cover glass and measured the instantaneous radiation incident Pel and the electric power supplied from the module. The expression for Tc, however, presupposes knowledge Pel is available during the relevant time, an element that must also be measured or, where possible, estimated using appropriate models (as a function of Ta and Gg (G), see also technical report).

3.2 Development to obtain Tc and Tg

In the following paragraph, the model is examined further and compared with the measurement campaign made. The comparison is done with the series of data obtained for the day 18.11.99, 9:30 am until to 14:30, a day of beautiful weather with instantaneous global radiation incident on the module to G 960 W/m2. During the measurement campaign was registered data every minute. Given the beautiful day for the calculation of Tc, was assumed that the global radiation measured in the whole match to direct sunlight (calculating the product (ζα) depending the angle of incidence). During the period measuring the PV module doesn´t produced electrical power (Pel = 0), something that has allowed to verify the optimum mode of heat loss of the same (reached equilibrium, all the solar power absorbed is lost as heat).

For comparison of the measured data, was determined with those calculated for the measures, an average value for interval of 30 min. For each interval, knowing the slope of the form (β = 64 °) and the respective geographical position, was calculated the angle of incidence corresponding to the average solar irradiation measured (in the form). Moreover, the PV module was used, based on materials which make the following optical and thermal parameters of the elements:

- Coefficient of thermal conductivity of glass cover: λg = 0.8 W/ m°C (can vary for a normal glass, 0,8-1.4 W/ m °C, depending on the type of glass).

- Extinction coefficient of glass ("water white") *: K* = 4 m^{-1}

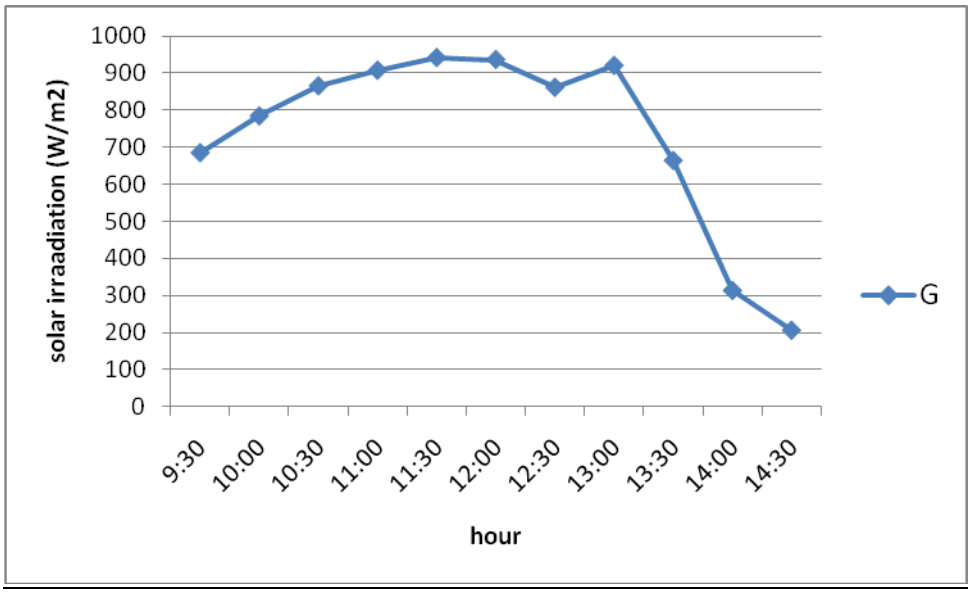
- Thickness of cover glass: δg = 6 mm.
  Coefficient of thermal conduction layer of plastic on the back of the form (tedlar): λp = ca. 0.4 W/ m ° C

- Thickness of the back cover of the form: δp = 2 mm.

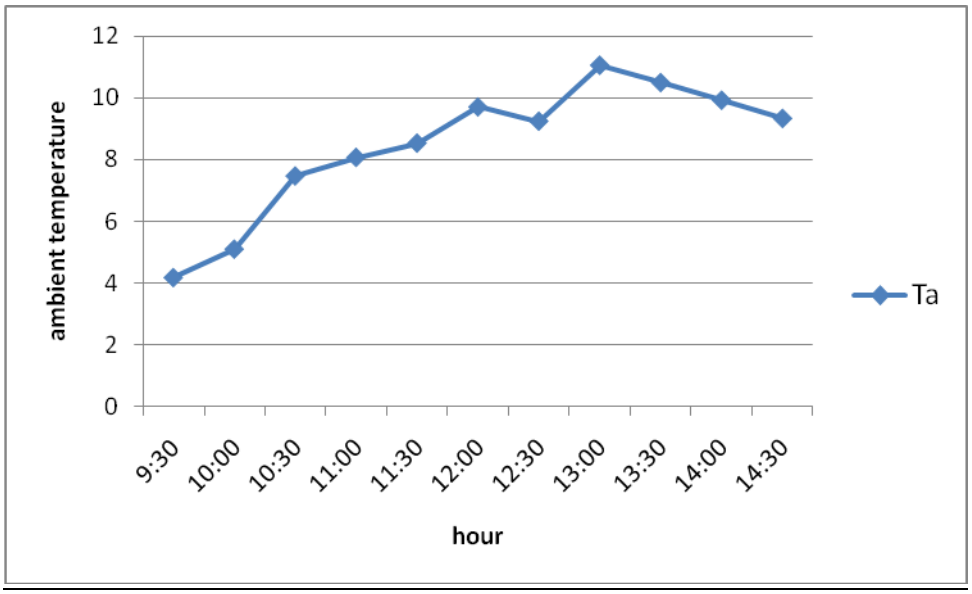
- Cells: form solution, absorption estimated, approx. 0.9 - 0.95, depending on the angle of incidence solar radiation.

- Hu was given a coefficient = (α; cv,u + α; irr,u) = 6 W/ m^2 °C (convection coefficient and radiation back side of form).

The values of solar irradiation (G) and ambient temperature (Ta) from different hours



Graphic 3.1



Graphic 3.2

3.2.1 Calculation of Tc and Tg without Pe

Supposing steady state equilibrium do you have the following equation:

$$A*G2 = A * P2 + A * P3 + Pt + Pe$$

Where Pt = 0 and Pe = 0. Eliminating de surface for the equation:

$$A*G2 = A * U2 (Tc – Tg) + A * U3 (Tc – Ta)$$

$$P = U2 (Tc – Tg) = U1 (Tg – Ta) \rightarrow p = Ueq (Tc – Ta)$$

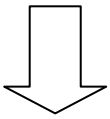
As the resistances are in sequence:

$$Ueq = 1 / Req = 1 / (R1 + R2) = 1 / ((1/U1) + (1/U2))$$

$$Ueq = (U1 * U2) / (U1 + U2)$$

$$G2 = (\zeta\alpha) * G = Ueq (Tc – Ta) + U3 (Tc – Ta)$$

$$(\zeta\alpha) * G = (Tc – Ta) + (Ueq – U3)$$



Tc is only unknown because G,Ta, (ζα), U1, U2,and U3 are given.

When you obtain de value of Tc you can calculate the value of Tg with this equation : $U2 (Tc – Tg) = U1 (Tg – Ta)$

GIVEN:

$(\zeta\alpha) = 0.85$

G, Ta = in the table

$U1 = 22{,}5\ W / m^2\ ºK$

$U2 = 135\ W / m^2\ ºK$

$U3 = 6\ W / m^2\ ºK$

Knowing the instantaneous radiation ,we have a lineal equation with one unknown (Tc) and it is very simple to obtain it. The results shown in table for cell temperature (Tc, calc), made directly compared with the measured temperature of the cell Tc,mis:

hour	**G** (W/m²)	**Ta** (ºC)	**Tc calc** (ºC)	**Tc mis** (ºC)
9:30	685	4,18	27,19	28,25
10:00	784	5,1	31,44	36,77
10:30	865	7,47	36,53	40,96
11:00	907	8,07	38,55	39,71
11:30	941	8,53	40,15	37,93
12:00	936	9,7	41,15	42,75
12:30	861	9,24	38,17	40,64
13:00	920	11,05	41,96	45,27
13:30	664	10,49	32,80	36,72
14:00	314	9,92	20,47	25,44
14:30	207	9,33	16,29	19,1

Table 3.1 Comparison of calculation results for Tc with data measured at 18.11.99, an average value for every 30 min.

Table legend:

G = instantaneous global solar radiation in W/ m² incident on the module .

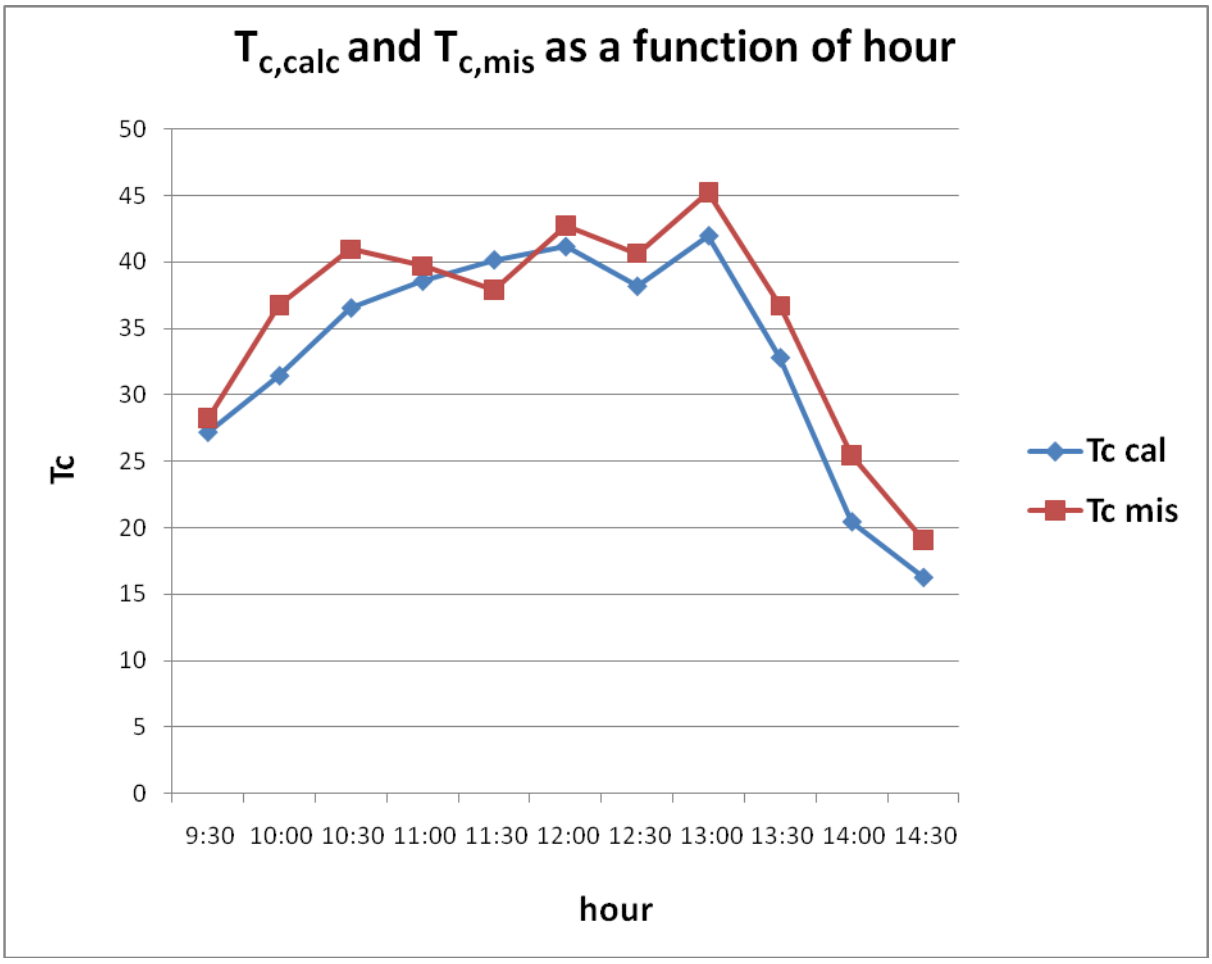
Ta = ambient temperature.

Tc,calc = cell average temperature.

Tc,mis = measured cell temperature.

We can see who Tc,calc and Ts,mis are similar and that tell us that the results are good. Also we can see who, when G have a big change Tc change very quickly.

The graph shows the growth temperature Tc measured and calculated and corresponding with instantaneous solar radiation as a function of time, here you can see even better collimation measured data with those calculated.



Graphic 3.2

It is important to remember that the quality of the results obviously depends on the quality parameters used in the calculation model. As such it is very important that the thermal parameters of materials component form, the value of thermal conductivity and thickness of the elements, as these directly establish the magnitude of the thermal resistances shown in Figure 3.1.

After that we obtain Tc we can calculate Tg. The results of Tg we can shown in this table where is compared with Tg,mis and with Tc,calc.

Hour	G (W/m²)	Ta (ºC)	Tc calc (ºC)	Tg calc (ºC)	Tg mis (ºC)
9:30	685	4,18	27,196	23,904712	25,94
10:00	784	5,1	31,4424	27,6754368	34
10:30	865	7,47	36,534	32,377848	37,86
11:00	907	8,07	38,5452	34,1872464	36,01
11:00	907	8,07	38,5452	34,1872464	36,01
12:00	936	9,7	41,1496	36,6523072	38,55
12:30	861	9,24	38,1696	34,0326672	36,72
13:00	920	11,05	41,962	37,541584	40,93
13:30	664	10,49	32,8004	29,6100128	33,6
14:00	314	9,92	20,4704	18,9616928	24,15
14:30	207	9,33	16,2852	15,2906064	18,31

Table 3.2

Table legend:

G = instantaneous global solar radiation in W/ m² incident on the module.

Ta = ambient temperature.

Tc,calc = cell average temperature.

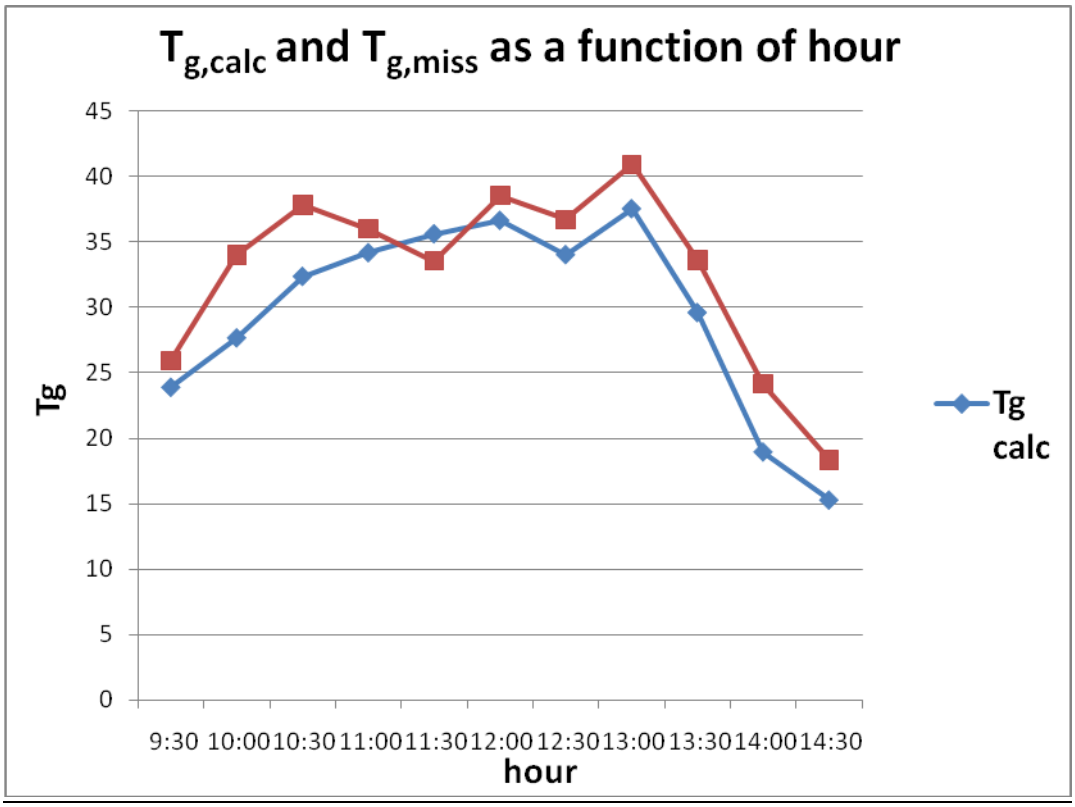
Tg,calc = glass average temperature.

Tg,mis = measured glass temperature.

We can see that there are large differences between Tg,calc and Tg,mis, but there aren`t so large, as to say that the calculations are wrong.

Temperature differences between the cover glass (Tg,calc) and the solar cell temperature (Tc,calc) calculated, ranging around 0.99 °C, the smallest,from approx. 4.5 °C, the biggest difference.

The graph shows the differences between the temperatures Tg,calc and Tg,mis.



Graphic 3.3

Temperatures are higher at midday after twelve o`clock. We can see that the two lines follow the same path more or less, although the points there aren`t very similar. Failure can come in that we have not taken Pe into account.

3.22 Calculation of Tc with Pe ($\gamma = 0$)

Supposing steady state equilibrium do you have the following equation:

$$A*G2 = A * P2 + A * P3 + Pt + Pe$$

Where Pt = 0 :

$$A*G2 = A * U2 (Tc – Tg) + A * U3 (Tc – Ta) + Pe$$

$$p = A*U2 (Tc - Tg) = A*U1 (Tg - Ta) \rightarrow p = A *Ueq (Tc - Ta)$$

As the resistances are in sequence:

$$Ueq = 1 / Req = 1 / (R1 + R2) = 1 / ((1/U1) + (1/U2))$$

$$Ueq = (U1 * U2) / (U1 + U2)$$

$$G2 = A * (\zeta\alpha) * G = A* Ueq (Tc – Ta) + A* U3 (Tc – Ta) + Pe$$

$Pel = I_M * V_M$

$$I_M = I_0 * (G2/G0) * (1 + \gamma (T_c - T_{ref}))$$

$$V_M = V_0 * (1 + \beta (T_c - T_{ref}))$$

$G2 = (\zeta\alpha) * G$ where $(\zeta\alpha) = 0,85$

$\beta = - 5 \times 10^3$

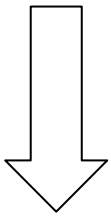
$V_0 = 36,80$ V

$I_0 = 4,9$ A

$G_0 = 1000$ W/ m^2

Tref = 25 ºC

$$A* (\zeta\alpha) * G = A * Ueq (Tc - Ta) + A* U3 (Tc – Ta) * Pe$$



Tc only unknown

GIVEN:

A = 1,3 m^2

(ζα) = 0.85

G, Ta = in the table

U1 = 22,5 W / m^2 ºK

U2 = 135 W / m^2 ºK

U3 = 6 W / m^2 ºK

An easier way to calculate the temperature Tc is using the NOCT temperature expression, given by:

12) $Tc^* = Ta + ((NOCT - 20) / 800) * G$

Where NOCT is the measured temperature of the plate under particular conditions. The value found of Tc is quite difference to the real value with some weather conditions, and therefore this expression can be used in order to find a first iterative value of temperature Tc. In this case we take NOCT = 45 °C.

Knowing the instantaneous radiation and ambient temperature, were obtained the results shown in table 3.3 for cell temperature (Tc,calc), made directly compared with the temperature of the cell (Tc*) calculated as we have seen:

hour	G (W/m²)	Ta (ºC)	Tc calc (ºC)	Tc* (ºC)
9:30	685	4,18	23,99	25,58
10:00	784	5,10	27,85	29,60
10:30	865	7,47	32,66	34,50
11:00	907	8,07	34,53	36,41
11:30	941	8,53	36,01	37,94
12:00	936	9,70	37,06	38,95
12:30	861	9,24	34,35	36,15
13:00	920	11,05	37,96	39,80
13:30	664	10,49	29,79	31,24
14:00	314	9,92	18,97	19,73
14:30	207	9,33	15,28	15,79

Table 3.3

Table legend:

G = instantaneous global solar radiation in W/ m² incident on the module .

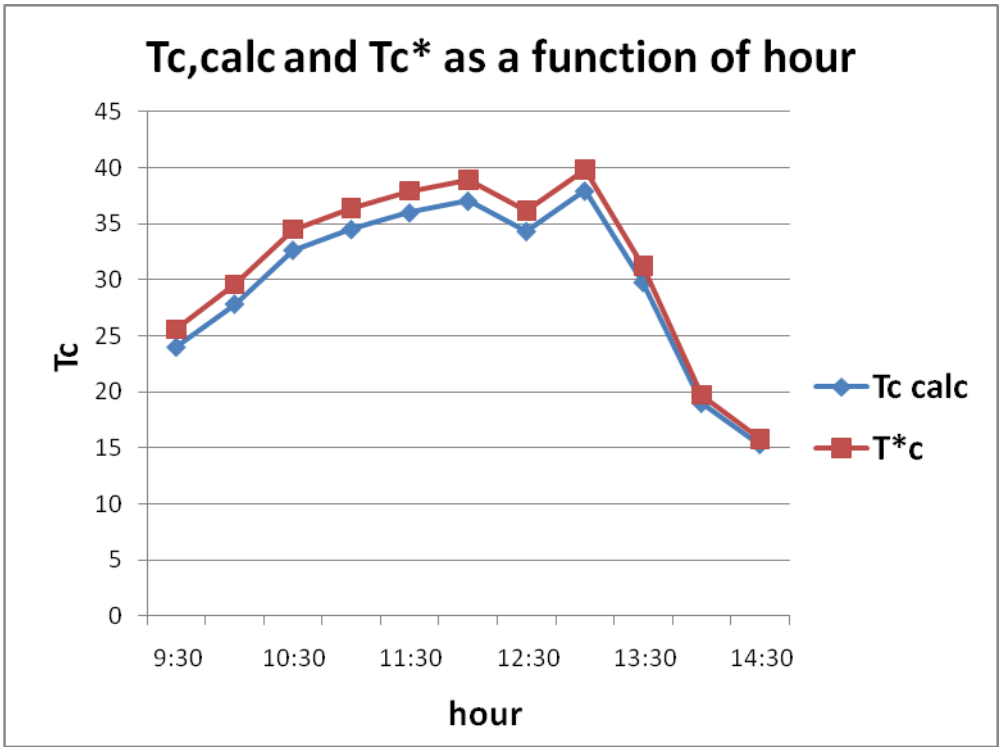
Ta = ambient temperature.

Tc,calc = cell average temperature.

Tc* = cell temperature calculate with NOCT expression.

In the table 3.3 we can see how the values of Tc,calc and Tc* are very similar. The differences are very small between them. That differences are small tells us that the calculations are well done. Differences ranging from 0.51 ºC to 1.88 ºC.

The graph shows the differences between the temperatures Tc,calc and Tc*.



Graphic 3.4

In the graph 3.4 you can see better that the differences of the temperatures are very small and they have the same trend during the whole graph. Tc,calc is bigger than Tc*. We can observe how the differences between the temperatures are larger in the beginning, because along passing the day the temperatures are more similar nearly equal.

3.2.3 Calculation of Tc with Pe ($\gamma \neq 0$)

Supposing steady state equilibrium do you have the following equation :

$$A*G2 = A * P2 + A * P3 + Pt + Pe$$

Where Pt = 0 :

$$A*G2 = A * U2 (Tc - Tg) + A * U3 (Tc - Ta) + Pe$$

$$P = A*U2(Tc - Tg) = A*U1\,(Tg - Ta) \rightarrow p = A*Ueq\,(Tc - Ta)$$

As the resistances are in sequence:

$$Ueq = 1 / Req = 1 / (R1 + R2) = 1 / ((1/U1) + (1/U2))$$

$$Ueq = (U1 * U2) / (U1 + U2)$$

$$G2 = A*(\zeta\alpha) * G = A * Ueq\,(Tc - Ta) + A* U3\,(Tc - Ta) + Pe$$

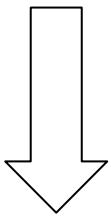
$$\mathbf{Pel = I_M * V_M}$$

$$I_M = I_0 * (G2/G0) * (1 + \gamma\,(T_c - T_{ref}))$$

$$V_M = V_0 * (1 + \beta\,(T_c - T_{ref}))$$

- $G2 = (\zeta\alpha) * G$ where $(\zeta\alpha) = 0{,}85$
- $\gamma = 5 \text{ X } 10^{-5}$
- $\beta = -5 \text{ x } 10^{3}$
- $V_0 = 36{,}80$ V
- $I_0 = 4{,}9$ A
- $G_0 = 1000$ W/ m^2
- Tref = 25 ºC

$$A*(\zeta\alpha) * G = A* Ueq\,(Tc - Ta) + A * U3\,(Tc - Ta) * Pe$$



Tc the only unknown

GIVEN:

$A = 1{,}3\ m^2$

$(\zeta\alpha) = 0.85$

G, Ta = in the table

U1 = 22,5 W / m² ºK

U2 = 135 W / m² ºK

U3 = 6 W / m² ºK

In this case we have a quadratic equation with only one unknown Tc. To do this we use excel program, because easier than if you done manually. And with excel we obtain the values of Tc,calc 1 at different hours. Tc* we obtain before with the lineal equation 12 before exposed.

Knowing the instantaneous radiation and ambient temperature, were obtained the results shown in table 4.

hour	G (W/m²)	Ta (ºC)	Tc calc (γ=0) (ºC)	Tc calc1 (γ≠0) (ºC)	Tc* (ºC)
9:30	685	4,18	23,99	24,00	25,58625
10:00	784	5,1	27,85	27,85	29,6
10:30	865	7,47	32,66	32,85	34,50125
11:00	907	8,07	34,53	34,51	36,41375
11:30	941	8,53	36,01	36,00	37,93625
12:00	936	9,7	37,06	37,04	38,95
12:30	861	9,24	34,35	34,34	36,14625
13:00	920	11,05	37,96	37,94	39,8
13:30	664	10,49	29,79	29,78	31,24
14:00	314	9,92	18,97	18,97	19,7325
14:30	207	9,33	15,28	15,28	15,79875

Table 3.4

Table legend:

G = instantaneous global solar radiation in W/ m² incident on the module .

Ta = ambient temperature.

Tc,calc = cell average temperature with $\gamma = 0$ (we obtain it before).

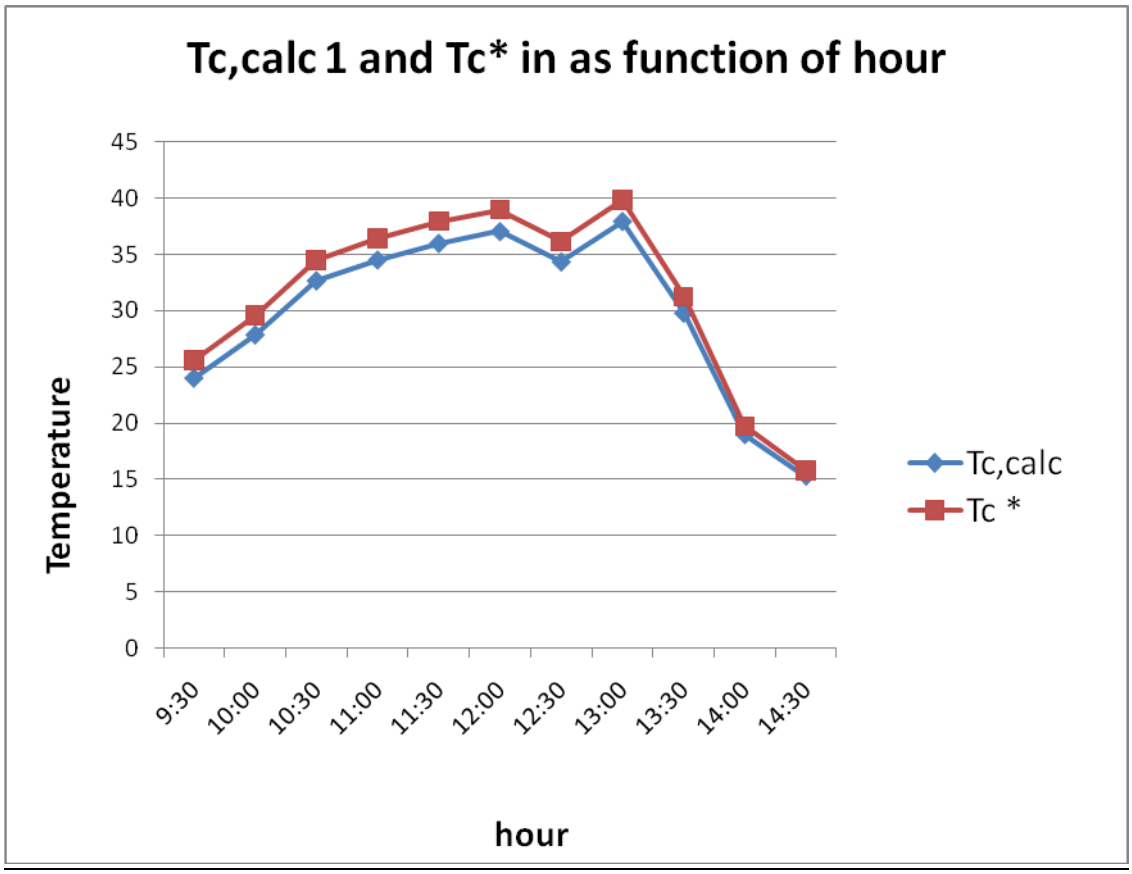
Tc,calc 1 = cell average temperature with $\gamma \neq 0$.

Tc* = cell temperature calculate with NOCT expression.

In the table 3.4 we can see how the values of Tc,calc 1 and Tc* are very similar. The differences are very small between them. That the differences are small tells us that the calculations are well done.

Observing the values of Tc,calc and Tc,calc 1 we see that they are very similar, being some values equals. This tells us that the value of γ is not important because that`s the only thing that has changed from one to another.

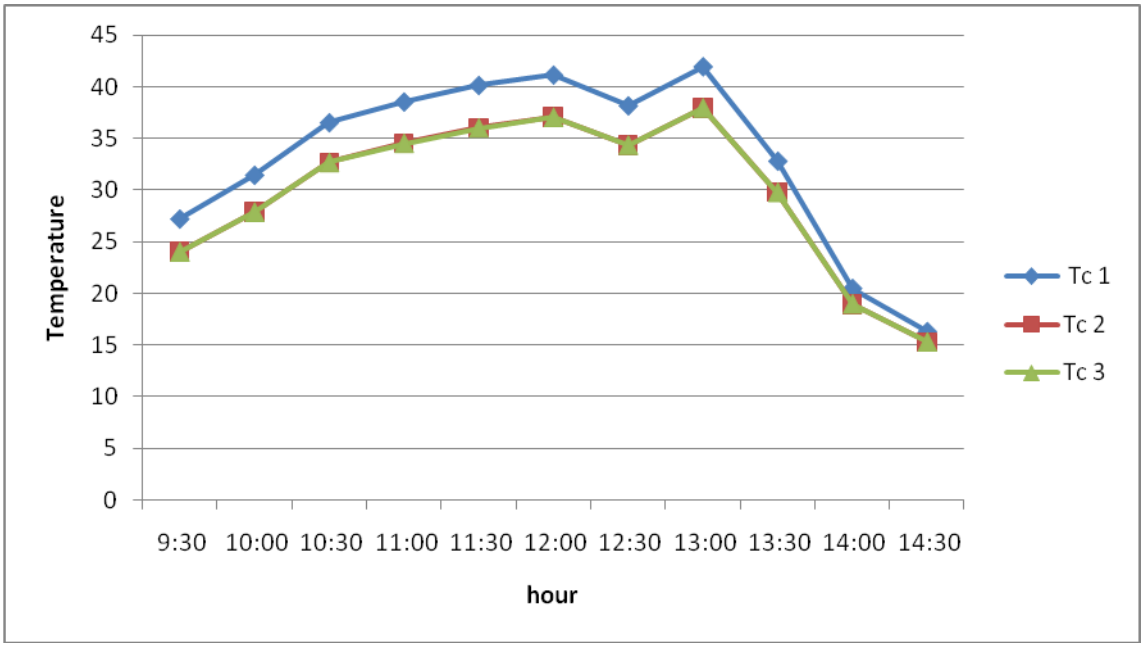
The graph shows the differences between the temperatures Tc,calc 1 and Tc*.



Graphic 3.5

In the graphic 3.5 you can see that the temperature differences are very small and that they have same trend during the whole graph. Tc,calc 1 is bigger than Tc*. We can observe how the differences between the temperatures are larger in the beginning, because along passing the day the temperatures are more similar, nearly equal . Graphic 3.4 and Graphic 3.5 are very similar because changes a little bit the temperature, hardly noticeable.

In the following graph we see the differences between the three Tc previously calculated, based on different data.



Graph 3.6

Tc1 = Tc calculated without Pe (electrical power).

Tc2 = Tc calculated with Pe, with $\gamma = 0$

Tc3 = Tc calculated with Pe, with $\gamma \neq 0$

As shown in the graph (3.6) the three lines have the same trends toward, but shows that if you catch Pe = 0 is different from the other two, a little more. This means that electric power causes the Tc temperature variety, among other variables.
As can be seen considering electrical power different to o the temperatures are lower. Comparing Tc2 and Tc3 shows that are almost equal and this says that the value of gamma (γ) isn`t very important in the values that can take it.

4. HYBRID SOLAR PANEL

4.1 Introduction

The Hybrid Solar panel is a thermal collector with PV cells, arranged on the absorber, resulting in a compact module with entry and exit for heat transfer fluid and a junction box for electrical wiring.

If we want the highest electrical and thermal energy per unit area operation is as follows:

The heat absorber which incorporates the Hybrid Solar Panel is crossed by a heat-bearing fluid which transfers its heat energy in a heat exchanger. The circulation of the fluid can be do it by thermosyphon or forced circulation. The maximum efficiency in photovoltaic system installations is obtained direct transfer without heat storage. Normally, the adhesive used for pasting solar cells is characterized by high thermal conductivity and good electric insulating material. To begin the study we can start by analyzing the components of the device .The hybrid collector is formed essentially by two main elements: a) the photovoltaic panel; b) the refrigeration system.
First we analyze the hybrid panel, which consists of these elements:

- Glass cover
- Insulation
- Frame
- Photovoltaic plate (PV)
- Absorber plate
- Piping (heat exchange tube)
- Insulation
- Frame

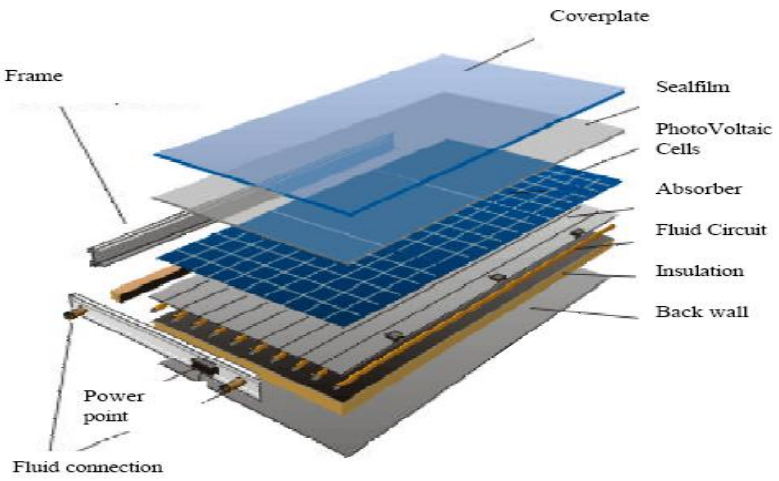


Figure 4.1 Exploded view of a generic hybrid pane

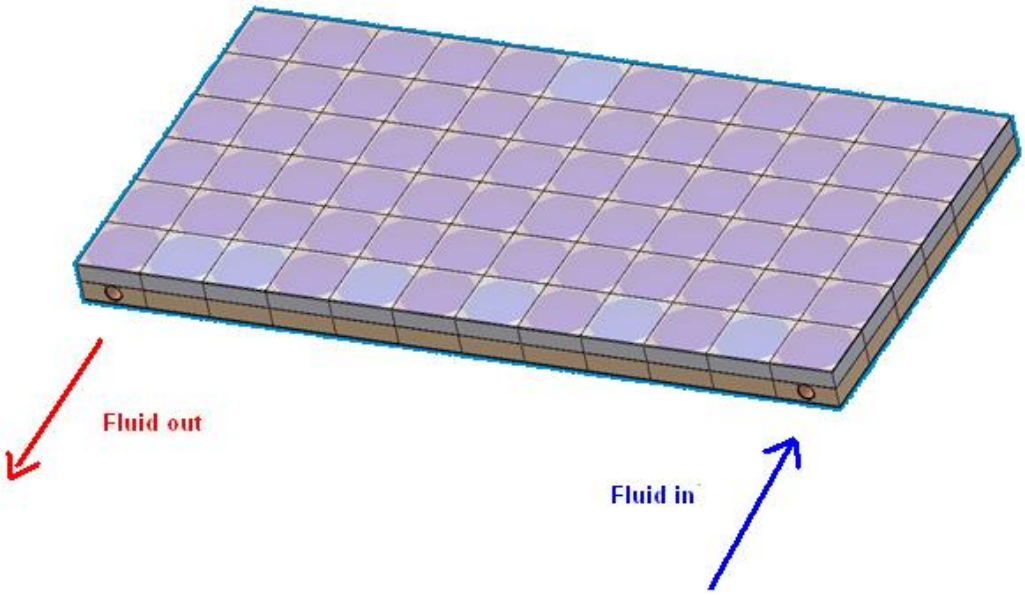


Figure 4.2 3D representation of a photovoltaic-thermal panel

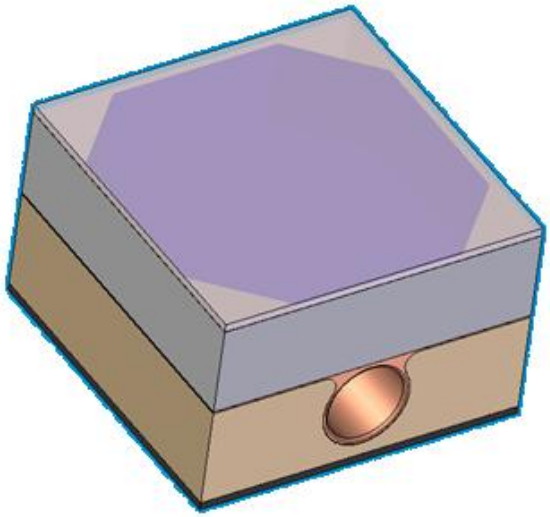


Figure 4.3 prospect of a photovoltaic-thermal hybrid cell.

The two basic applications that Hybrid Solar Panel has, are:

1) Used in buildings, is able to produce electrical energy more efficiently, increasing by at least 15 % more than traditional PV panels and at the same time in the same space, heats water for sanitary purposes, swimming pools, heating, etc……That is a solar panel with cogeneration.

Figure 4.4 Here we can see an installation of hybrid solar panel in a house.

2) The use of these panels in solar farms, increased electricity production more than 15%, achieving yields so far unattainable. In this case the hybrid solar panel is used as photovoltaic module cooled, missing hot water and concentrating all its role in electricity production.

If the hybrid solar panel is used as a cooled photovoltaic module, like a second application, the operation is as follows:

The electrical system with refrigerated unit does not suffer significant change at this level. What it changes is that you must add a hydraulic circuit comprising supply and return pipes through which circulates a heat-bearing fluid that runs through the absorbers integrated photovoltaic modules. The fluid that it returns from the photovoltaic generator transfer the heat to a cooling station consists of coolers, air cooled by convection or forced ventilation. Round pipes must be thermally insulates to prevent heating with solar radiation. The return pipe may contain cooling fins and / or may be buried to dissipate heat more efficiently.

In PV/T system applications, considering that the electricity is of priority, then the operation of the PV modules at lower temperatures is necessary in order to keep PV cell

electrical efficiency at a sufficiently higher level. This demand limits the operation range of PV/T system thermal unit in lower temperatures and the extracted heat can be mainly used for low temperature thermal needs.

The solar energy captured by the Hybrid Solar Panel is distributed as follows:

As is well known, the spectrum of solar radiation exploited varies from infrared to ultraviolet. Interestingly photovoltaic modules work best in the high end of the spectrum, namely the ultraviolet environment. Infrared radiation does not increase the production of electricity, rather the opposite, provides heat, which is a negative effect on efficiency.
In thermal collectors is precisely the environment to the infrared spectrum which contains the energy to be harnessed to heat water, while ultraviolet radiation contributes virtually nothing.
As can be inferred from this reasoning, each system by itself takes only part of the spectrum, while together they form a whole that takes virtually all the energy contained in sunlight, from infrared to ultraviolet.

4.2 Different types

1) Hybrid PV/T systems with air heat extraction

2) Hybrid PV/T systems with water heat extraction

Hybrid PV/T systems with air heat extraction are more extensively studied because of their easier construction and operation. Hybrid PV/T systems with water heat extraction is more expensive but water from mains is usually under 20 degrees and therefore in most applications water heating is useful during all seasons. PV/T systems with air or water heat extraction could be cost effective, if the additional cost of the thermal unit is low and the extracted heat is effectively used.

Cox and Raghuraman presented numerical methods of predicting the performance of both air and liquid PV/T collectors. Their studies suggested that PV/T air collectors were thermally less efficient than PV/T collectors using water as the heat transfer fluid due to the lower absorber to air heat transfer coefficient.

We have studied the second type, PV/T water systems with water heat extraction. The fluid is not circulated in direct thermal contact with the PV rear surface because of potential problems with the electrical conductivity of the PV module. To avoid these problems the water must circulate through pipes of reasonable diameter in contact with the PV module rear surface. In PV/T systems the thermal unit for water heat extraction,

the necessary pump and the external pipes for fluid circulation constitute the complete system that extracts the heat from PV module and brings it to the final use.

There are two types, with water heat extraction:

a) CONTACT type PV/T

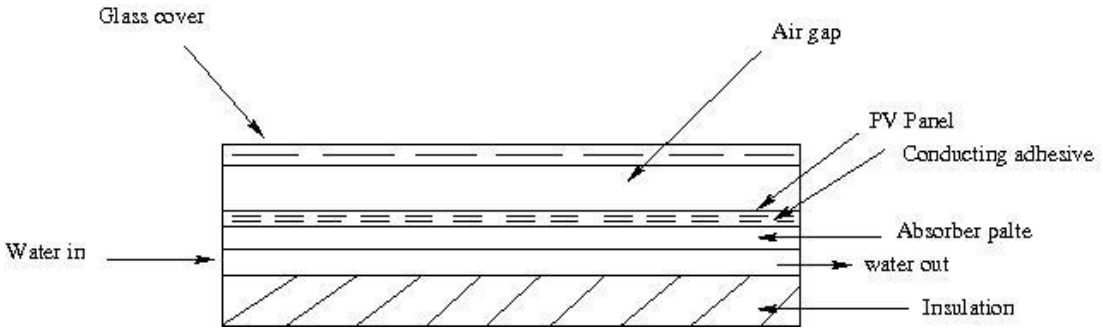


Figure 4.5

b) NON-CONTACT type PV/T

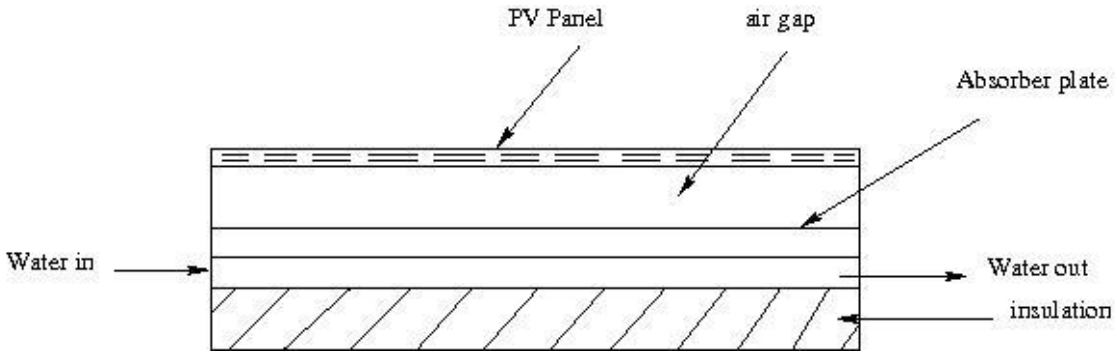


Figure 4.6

The conceptualized non-contact Photovoltaic-Thermal (PV/T) collector consists of PV panel separated by a conventional sheet and tube solar thermal collector. Simulation of both non-contact type and contact type collectors is carried out and correlations are proposed for both thermal and electrical efficiencies in terms of irradiation, inlet water temperature, ambient temperature and PV transmissivity. At high values of transmissivity (ζ higher than 0.75), the thermal efficiency of the non-contact type system exceeds that of the contact type collector at higher values of inlet temperatures. The PV/T system yields thermal and electrical efficiencies in order of 30-35% and 8-9% respectively. Experiments are carried out to validate the simulation results and to study the influence of performance parameters.

4.3 Mathematical model

Contact type PV/T System has been considered, because it can perform better than the contact type collector at high water inlet temperatures and high PV panel transmissivity values. The mathematical model of the electric and thermal system has been carried out, in order to find the performance of the hybrid systems under the different weather conditions, and in order to analyze the influence of the main important parameters on the thermal and electric efficiency. The strategy of lowering the PV plate temperature is important in order to increase the electric power production, obtaining also thermal power which could be used to satisfy domestic thermal demand. Another positive consequence of this approach is connected to the PV plate material, Which will last much more at low temperatures.

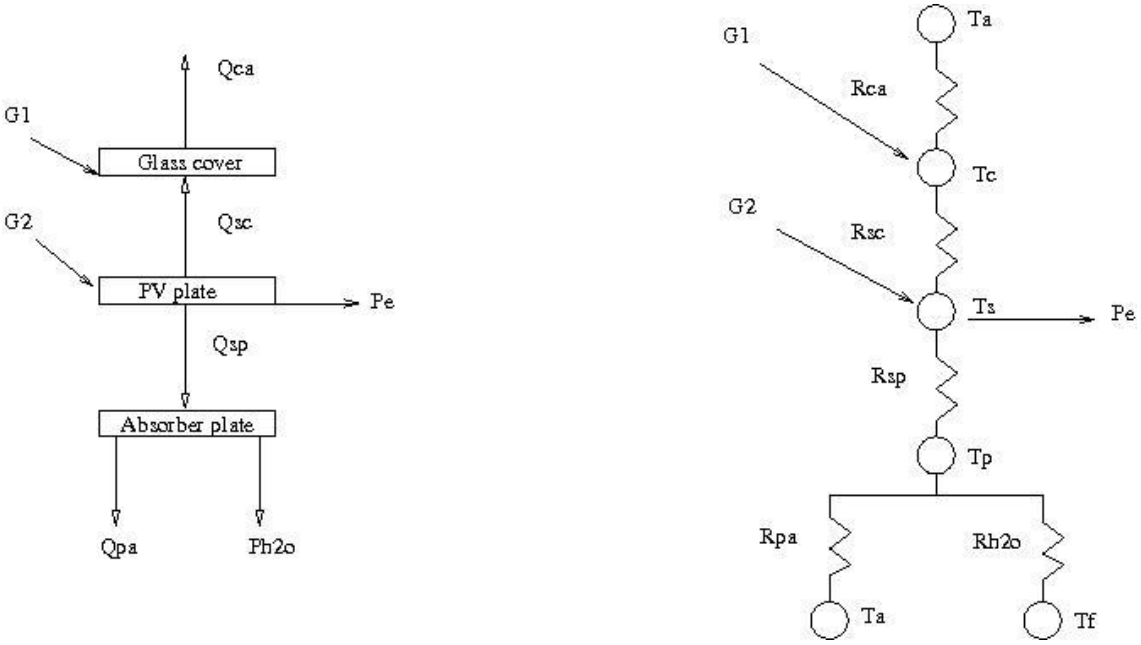


Figure 4.7 Thermal network of a PV-T collector.

An electrical model for the heat losses and energy balance for contact type hybrid collector is given. In figure 4.7 the thermal equivalent network of the system is shown.

Nomenclature:

A = collector surface area (m^2)

c_{H2O} = Specific heat (J/kg°K)

F' = Shape factor

F = Collector efficiency factor

G = solar irradiance (m^2)

G_1 = is the power absorbed by de glass cover, which can be neglected ($G_1 = 0$).

G_{H2O} = Mass flow rate (Kg/ m^2s)

h = Heat transfer coefficient (W/$m^{2\circ}$K)

h_w = Convective heat loss coefficient due to wind (W/$m^{2\circ}$K)

I_M = maximum current (A)

Nuss = Nusselt Number

Pe = electric power (W)

P_{H2O} = water power (W)

Pr = Prandtl Number

Q = Power (W)

Ra = Rayleigh Number

T = Temperature (°K)

U = Total heat transfer coefficients (W/$m^{2\circ}$K)

v = wind speed (m/s)

V = maximum current (V)

E = Emissivity

γ = Kinematic viscosity (m^2/s)

Sigma = Stefan Boltzmann Constant (W/m^2 °K^4)

β = Collector tilt angle (degree)

Subscripts:

a = ambient

c = glass cover

f = working fluid

fi = inlet fluid

fo = outlet fluid

fm = mean fluid

p = absorber

r = irradiative

s = solar cell

Supposing steady state equilibrium, the following equations comes out from the heat balances:

The four main equations are as follows:

$$\begin{cases} 1)\ A*G_1 + Q_{sc} - Q_{ca} = 0 \\ 2)\ A*G_2 + Q_{sc} - Q_{sp} - P_e = 0 \\ 3)\ Q_{sp} - Q_{pa} - Q_{pf} = 0 \\ 4)\ Q_{pf} - P_{H2O} = 0 \end{cases}$$

1) $\underline{A*G_1 + Q_{sc} - Q_{ca} = 0}$

A = collector surface area (m^2)

G_1 = 0

Qsc = A * Usc * (Ts – Tc)

Usc = hsc + hrsc

$$hsc = \frac{0.027 * Nuss}{0.03}$$

$$Nuss = 1 + 1.44\left[\frac{[z1] + z1}{2}\right] * \left[1 - \frac{1.708 * (sen1{,}8\beta)}{Ra * \cos\beta}\right] + \left[\frac{[z2] + z2}{2}\right]$$

$$z1 = 1 - \frac{1708}{Ra * \cos\beta}$$

$$z2 = \left[\left(\frac{Ra * \cos\beta}{5830} \right)^{\frac{1}{3}} - 1 \right]$$

$$Ra = \frac{2 * g * (Ts - Tc) * \zeta^3 * \Pr}{\gamma^2 * (Tc + Ts)}$$

$$\gamma = \gamma o \left[\frac{Tmsc}{288} \right]^{2,5} * \left[\frac{288 + 110}{Tmsc * 110} \right]$$

$$Tmsc = \frac{Tc + Ts}{2}$$

$$hw = 5.7 + 3.8 * Vw$$

Qca = A * Uca * (Tc – Ta)

Uca = hrca + hw

$$hrca = Epsc * \theta * \left[\left(Tc^2 + Tsky^2 \right) \left(Tc + Tsky \right) \right]$$

$$hw = 5.7 + 3.8 * Vw$$

2) <u>A*G_2 + Q_{sc} – Q_{sp} – P_e = 0</u>

G2 = (ζ * α)* G

Q_{sc} explained above

Q_{sp} = A * U_{sp} * (Ts – Tp)

Usp = λ_{plast} / θ_{plast}

As in our case the conduction is in plastic material: $\lambda_{plast} = 0.2$ and $\theta_{plast} = 0.001$

Therefore Usp = 0.2 / 0.001 = 200

$Pe = I_M * V_M$

$I_M = I_0 * (G2/G0) * (1 + \gamma (T_s - T_{ref}))$

$V_M = V_0 * (1 + \beta (T_s - T_{ref}))$

The parameters are defined on page 35.

3) $\underline{Q_{sp} - Q_{pa} - Q_{pf} = 0}$

Q_{sp} explained above.

$Q_{pa} = A * U_{pa} * (Tp - Ta)$

In our case Upa = 6 ($W/m^2 K$)

$Q_{pf} = A * F' * (Q_{sp} - U_{pa} * (Tfm - Ta))$

$$F' = \frac{1}{W * Upa} * \frac{1}{\left[\frac{1}{Upa * (D + (W - D) * F} + \frac{1}{\pi * Di * hfi}\right]}$$

$$F = \frac{tgh\left(\frac{m * (W - D)}{2}\right)}{\frac{m * (W - D)}{2}}$$

$$m = \sqrt{\frac{Upa}{\delta abs * \lambda abs}}$$

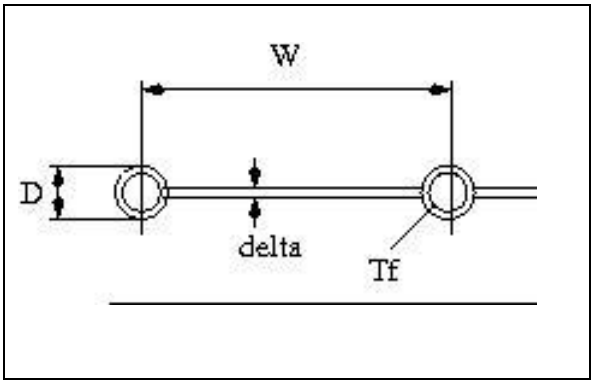


Figure 4.8 Refrigeration system.

4) $\underline{Q_{pf} - P_{H2O} = 0}$

Q_{pf} explained above.

$$P_{H2O} = G_{H2O} * C_{H2O} * (Tfo - Tfi)$$

$$Tfm = \frac{(Tfi + Tfo)}{2}$$

The total heat transfer coefficients U (Usc,Uca,Upa,Usp) are the inverse of the thermal resistance R appearing in figure 4.7. Those coefficients can be calculated according to the heat transfer mechanism operating in the considered part, that is to say conduction trough solid walls, convection and radiation in air gaps or at the top and bottom surface of the collectors. The radiations coefficients, which, as well known, are function of the difference of the 4th power of the two radiating plats temperatures, have been linearized , in order to have also for the radiation term the same dependence of the temperature difference as the convection mechanism.
Considering the PV generating system, it can be noted that usually the power given by the collector is the maximum one Pe, due to an appropriate control system.

4.4 Development to solve the system and results

1) Without refrigeration

Without refrigeration the four main equations that I commented before, become in one system of three equations and three unknowns (Tc, Ts, Tp) because the weather parameters (solar irradiance, ambient temperature and wind velocity..) are known. We have taken the ambient temperature constant (Ta = 20 ºC).

The three main equations are as follow:

1) $A*G_1 + Q_{sc} - Q_{ca} = 0$

2) $A*G_2 + Q_{sc} - Q_{sp} - P_e = 0$

3) $Q_{sp} - Q_{pa} = 0$

Secondary equations (Qsc,Qca….etc) are developed in Mathematical model part (page 46 - 49). The system of equations is non linear and in order to solve the system, an iterative, secant method has been chosen, which starts predicting the temperature Ts of PV panel, and evaluating at the end of the complete loop of calculation an opportune error, in our case in the third equation.

With this method and knowing the following data:

A = 1.3 m^2	g = 9.81 m/s^2	Pr = 0.72
δaria = 0.03	$\gamma_0 = 1.55x10^{-5}$	Sigma = $5.6704x10^{-8}$
λ_{aria} = 0.027	E_{psc} = 0.88	v = 1 m/s
Tsky = Ta = 20°C	E_{psp} = 0.95	Upa = 6 W/m^2 °K
Usp = 200 W/m^2 °K	β = 0	(ζ * α) = 0.8

We can solved the system in a computer program called **gfortran**. Once the system has been solved the electric efficiencies we can be calculated:

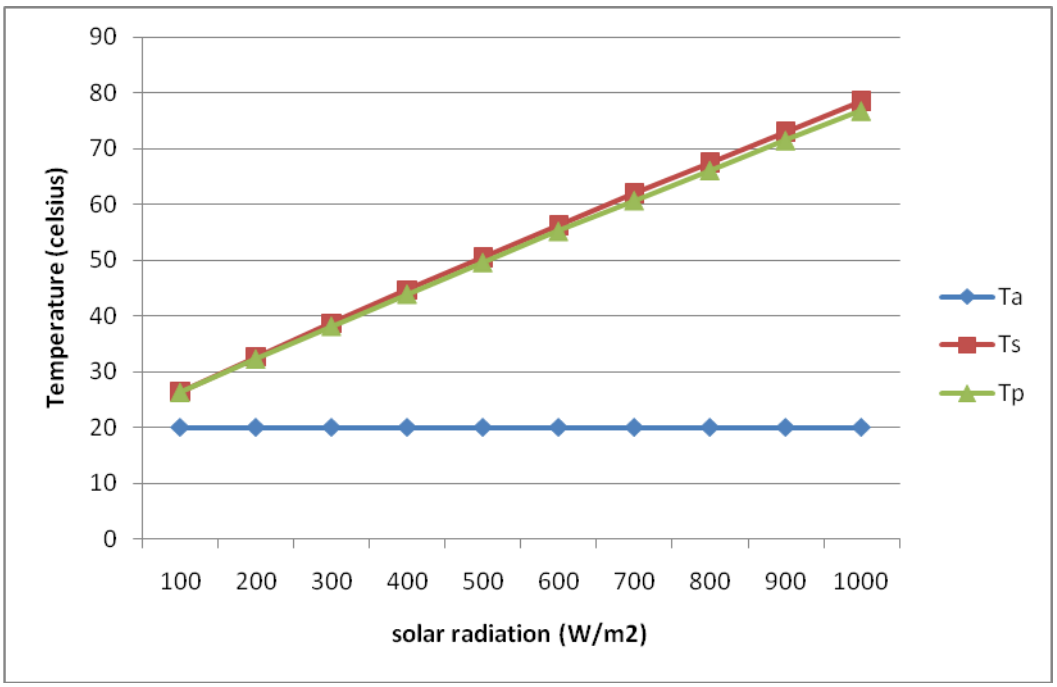
$$\eta_e = P_e / G$$

The results of the different temperatures with different values of irradiance, we can shown in table 4.1.

G	Ta	Ts	Tp	Tc
100	20	26,462	26,274	22,134
200	20	32,652	32,284	24,374
300	20	38,708	38,163	26,664
400	20	44,05	43,93	28,99
500	20	50,505	49,617	31,35
600	20	56,268	55,211	33,75
700	20	61,948	60,726	36,17
800	20	67,55	66,165	38,61
900	20	73,076	71,531	41,079
1000	20	78,531	76,826	43,566

Table 4.1

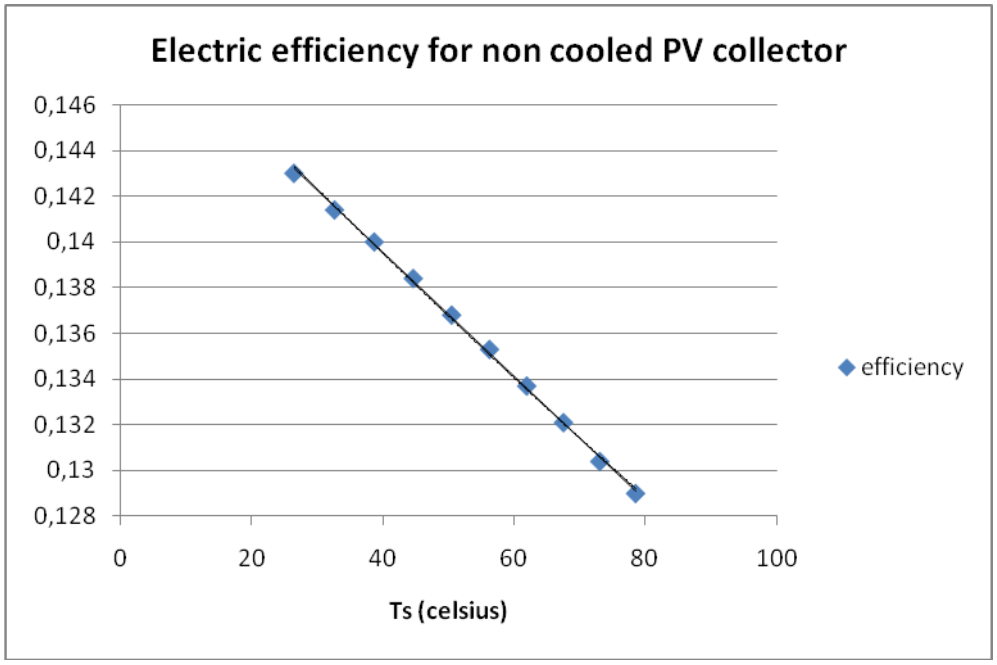
To analyze the effect of the cooling system on the performance of the PV cell, first we have to study the conduct of the cell without refrigeration but with absorber plate. And this can bee seen in the following graphs (4.1,4.2 and 4.3) and in the previous table.



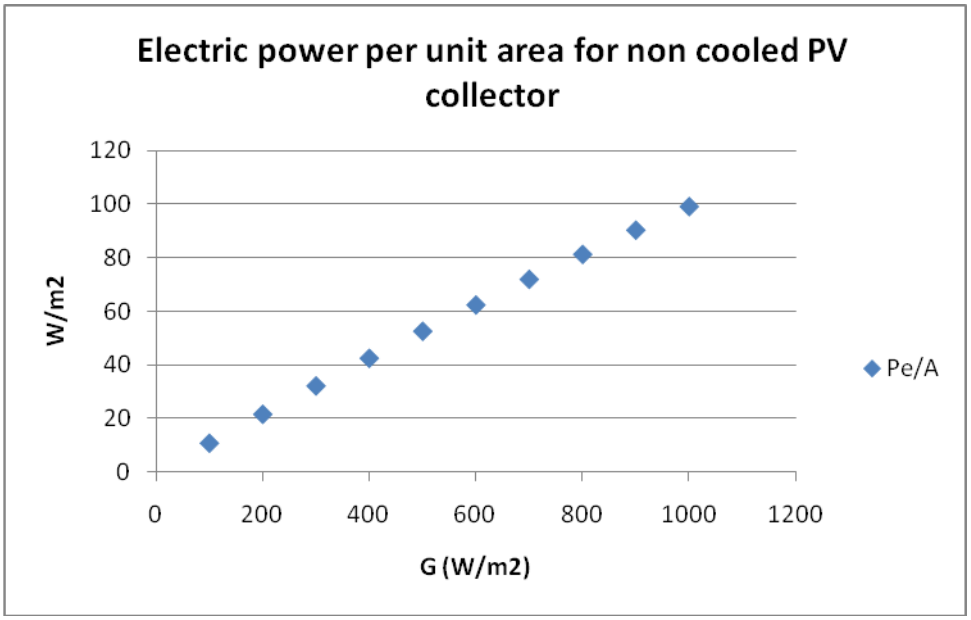
Graphic 4.1

In this graph we can shown the differences between Ts and Tp temperatures are very smalls, and differences of both (Ts,Tp) with Ta are bigger. The wall temperatures increase obviously with irradiance, reaching 80 ºC for G = 1000 W/m^2.

In the following graphics can be seen how changes electric efficiency when Ts varies and how changes electric power per unit area when varies the solar irradiance.



Graphic 4.2



Graphic 4.3

The electric power per unit area increases with irradiance, but no linear due to the effect of temperature, which tends to lower the power. In fact the efficiency of the system decreases with wall temperature, as can be seen in Graphic 4.2. This is the main reason why we have studied the hybrid solar panel, to lower temperature of the solar cell.

2) With refrigeration

With refrigeration, the system has all the equations that we explained before in the part of mathematical model (page 46 - 49).These are the four main equations of the system:

1) $A*G_1 + Q_{sc} - Q_{ca} = 0$

2) $A*G_2 + Q_{sc} - Q_{sp} - P_e = 0$

3) $Q_{sp} - Q_{pa} - Q_{pf} = 0$

4) $Q_{pf} - P_{H2O} = 0$

The system of equations is non linear ;Knowing therefore all the characteristic of the PV-T collector, and in particular geometry of the refrigerating tubes connected to the absorber plate and the weather conditions, the equations system can be solved if two of the external parameters are fixed. In the present paper the study have been carried out considering knowing the inlet water temperature **Tfi** and the water mass flow rate **Gh2o**. In order to solve the system, an iterative, secant method has been chosen, which starts predicting a temperature Ts of the PV panel, and evaluating at the end of the complete loop of calculation an opportune error function, in our case in the forth 4) equation.

With this method and knowing the following data:

$A = 1.3\ m^2$	$g = 9.81\ m/s^2$	$Pr = 0.72$
$\delta aria = 0.03$	$\gamma_0 = 1.55x10^{-5}$	$Sigma = 5.6704x10^{-8}$
$\lambda_{aria} = 0.027$	$E_{psc} = 0.88$	$v = 1\ m/s$
$Tsky = Ta = 20°C$	$E_{psp} = 0.95$	$Upa = 6\ W/m^2\ °K$
$Usp = 200\ W/m^2\ °K$	$\beta = 0$	$Gh2o = 0.05\ kg/s$
$c_{h2o} = 4186\ J/kg°K$	$Tfi = 25\ °C$	$(\zeta * \alpha) = 0.8$

(data to calculated F)

W = 0.8/11 di = 0.003m n = 11 (tubes number)

δ_{abs} = 0.003 m D=De = Di + 2* ζ λ_{abs} = 204 W/m°K

h_{fi} = 1500 π = 3.1416

We can solved the system in a computer program called gfortarn, with this condition: if Tfm is larger than Tp them Tfm = Tp. Because if Tfm if Tfm is larger than Tp the program don`t work. Once the system has been solved the electric efficiencies we can be calculated:

$$\eta_e = P_e / G$$

$$\eta_{th} = P_{h20} /G$$

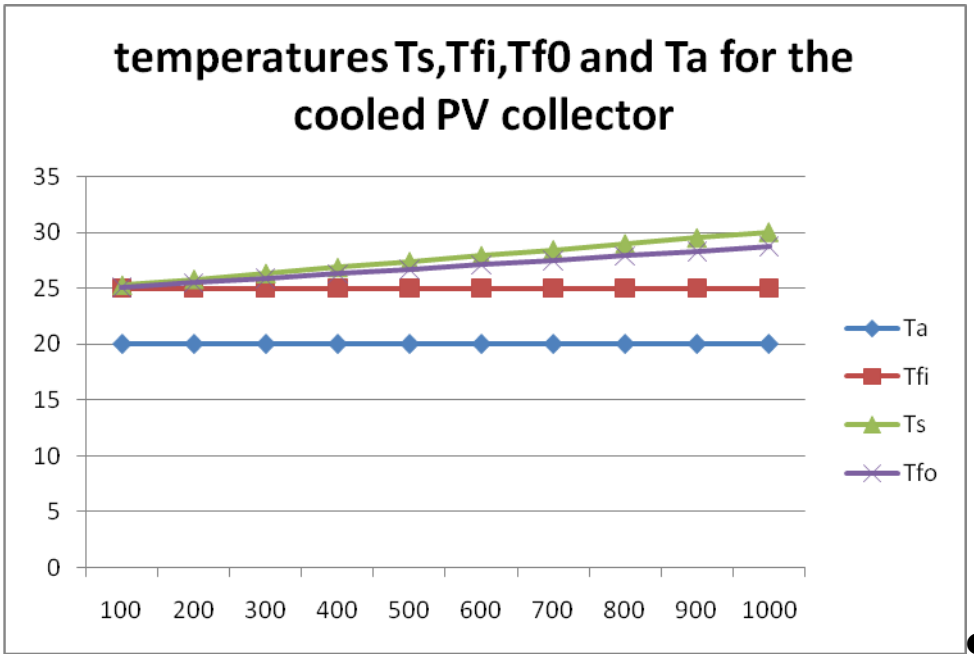
As pertains to the characteristics of the PV-module, a Trina Solar TSM_DC01 collector has been considered; this module has been modified adding in the lower part an absorber plate with 11 tubes.

The same parametric that we study to non cooled PV collector we study to cooled PV collector. We can see in the table below the temperatures of different parts of the collector and water outlet temperature varying the irradiance, for fixed values of Tfi = 25 ºC and Ta = 20 ºC.

G (W/m^2)	Ts	Tfo	Tp	Tc
100	25,261	25,084	25,042	21,715
200	25,792	25,487	25,243	21,899
300	26,324	25,889	25,445	22,085
400	26,86	26,292	25,646	22,27
500	27,387	26,695	25,847	22,461
600	27,92	27,1	26,048	22,65
700	28,451	27,501	26,25	22,84
800	28,98	27,903	26,45	23,04
900	29,514	28,306	26,653	23,224
1000	30,046	28,709	26,855	23,417

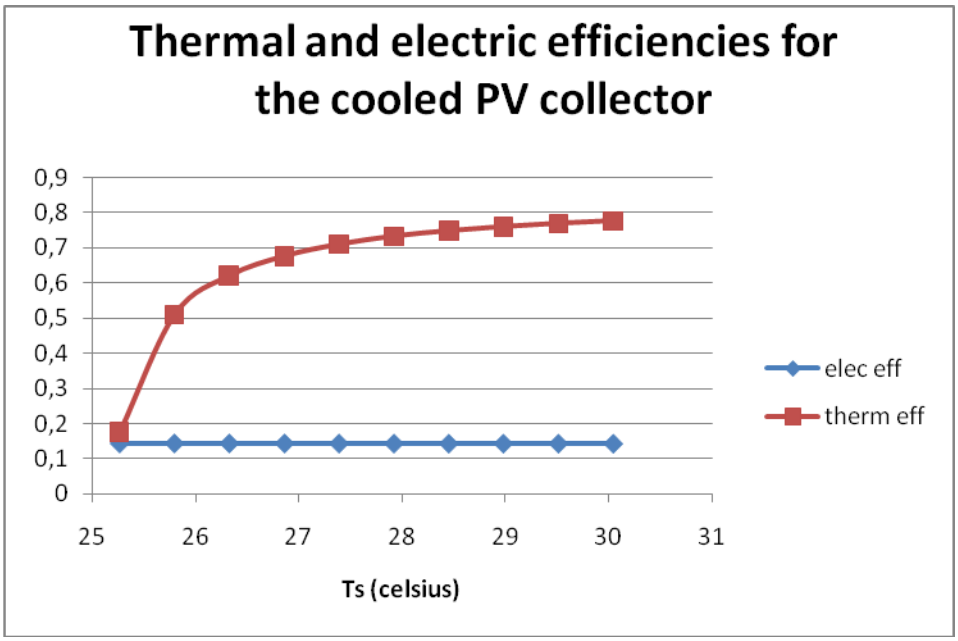
Table 4.2

With this information we have do the follow graphic, it shows the wall temperature Ts and the outlet temperature Tfo, with constant values of Tfi and Ta. It can be noted that the refrigeration system reduces the wall temperature in a considered way, if we compared these temperatures with the temperatures that we have obtained without refrigeration.



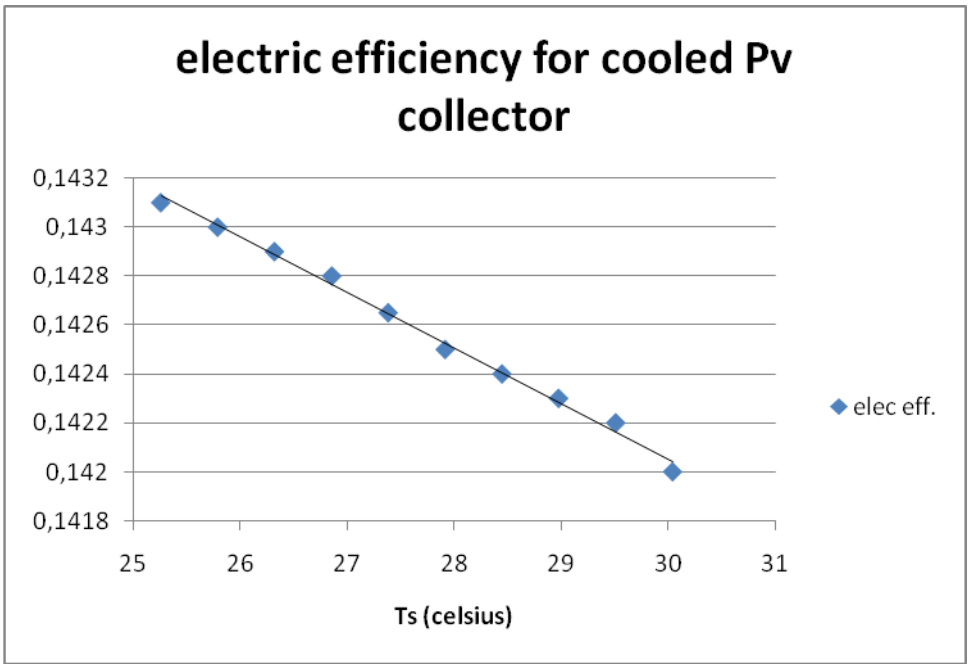
Graphic 4.4

In the following graphics can be seen how changes electric and thermal efficiency when Ts varies. The first graphic shows the big differences between the two efficiencies. The second graphic if we compared with the electric efficiency obtained without refrigeration we can so that how the temperatures without refrigeration are higher the electric efficiency is lower.



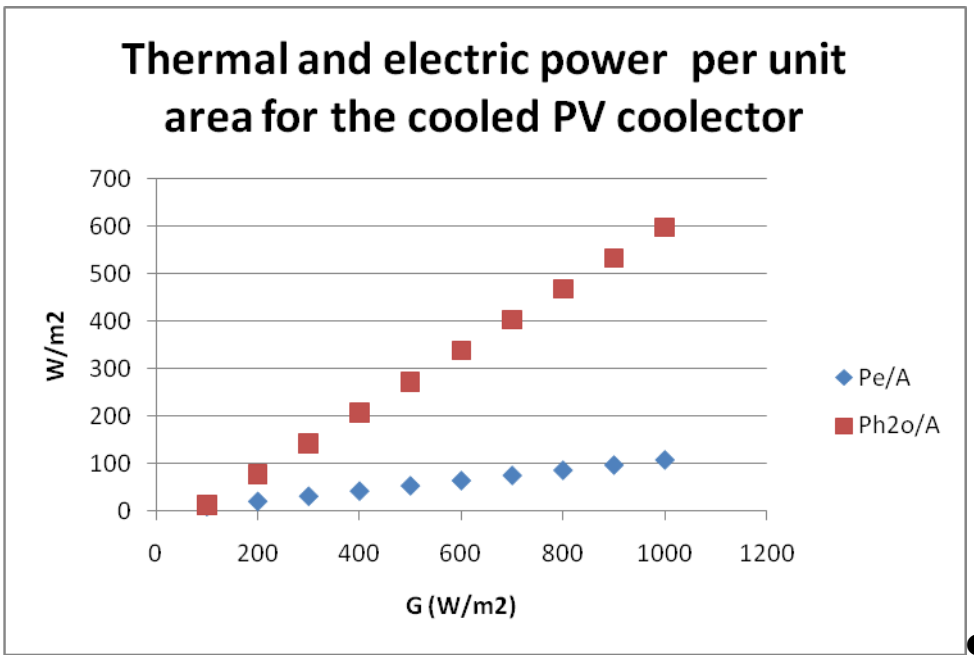
Graphic 4.5

In this graphic we can see that thermal efficiency is higher than the electric one. And the second difference is that when the temperature uploads the thermal efficiency rise and on the contrary when the temperature uploads the electric efficiency low. The rise of the thermal is much larger than the decrease of the electric. The decrease of the electric efficiency we can see in the following graphic.



Graphic 4.6

Graphic 4.7 shows how changes electric and thermal power (Pe and Ph2o) per unit area when the irradiance varies from 100 to 1000 W/m^2.

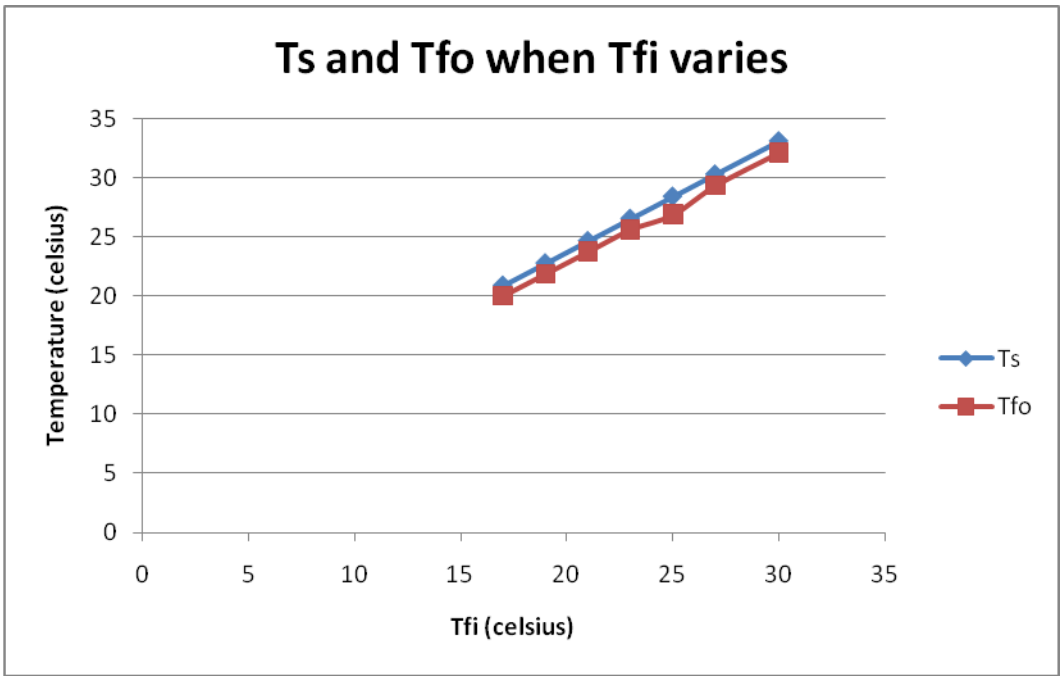


Graphic 4.7

In the table and graphic that we have below, we can see how varies the temperatures Ts, Tp, Tc and Tfo when we change the value of the temperature Tfi (inlet water temperature), maintaining constant G = 700 W/m^2 and Ta = 20 °C. We can observe that when Tfi upload, Tfo and Ts takes values more high also. And this is because the cooling water enters in the system with more temperature, and it can`t refrigerate like a water with less temperature. After the table we can see the graphic .

Tfi	Ts	Tfo	Tp	Tc
17	20,894	20,018	18,509	20,253
19	22,786	21,891	20,446	20,872
21	24,677	23,763	22,381	21,51
23	26,565	25,632	24,316	22,17
25	28,451	26,903	26,25	22,84
27	30,335	29,368	28,184	23,522
30	33,16	32,167	31,083	24,565

Table 4.3

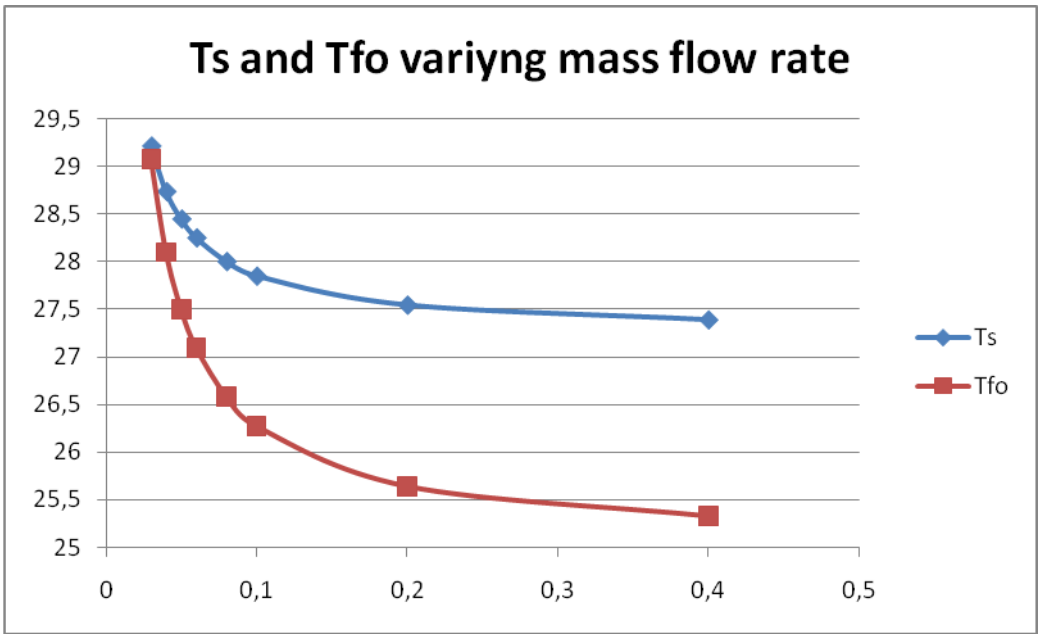


Graphic 4.8

To finish de analysis we are going to see how changes the temperatures Ts, Tp, Tc and Tfo when the mass flow rate (Gh2o) varies, maintaining constants the values of G = 700 W/m^2, Ta = 20 ºC and Tfi 25 ºC. We can see that, when the mass flow rate take high values the temperatures takes fewer values. For example to Tfo the explication is very simple, because when the mass flow rate is bigger we have more water to heat, therefore the temperature of Tfo is minor. And how is more water can refrigerate better and the others temperatures, like Ts, Tp or Tc are minor. After the table we can see the graphic with Ts and Tfo temperatures.

Gh2o	Ts	Tfo	Tp	Tc
0,03	29,219	29,077	27	23,117
0,04	28,74	28,1	26,55	22,945
0,05	28,451	27,501	26,25	22,84
0,06	28,253	27,095	26,047	22,77
0,08	28,003	26,582	25,791	22,681
0,1	27,85	26,271	25,635	22,626
0,2	27,544	25,64	25,32	22,537
0,4	27,388	25,327	25,16	22,461

Table 4.4



Graphic 4.9

5. CONCLUSION

The developed simulation model for predicting the transient performance of a hybrid PV/T forced circulation solar water heating system has been presented. The model can predict the performance of the system such as Tfo, η_e , η_{th} … etc for various weather conditions (G).

The conclusions that can be drawn from the above in this project are:

- If we refrigerate properly the cells of a PV panel, can achieve significant increases in electric power by them. Because a high values of temperature in the PV panel decreases much the electric performance of the PV panel as we have seen in the graphics.
- Installing a heat-absorbing in the backside of the PV solar panel, we can produce hot water, with sufficient efficiency to be utilized in applications of sanitary uses, heating, swimming pools,…etc. Or we can only refrigerate PV panel like in solar gardens where the solar hybrid panel is used as a photovoltaic module with refrigeration.
- It is possible to reduce the space required to install photovoltaic and thermal solar energy. Therefore less environmental impact.

We can also say for all we know and so we read that the life of the modules is higher most of all because the work temperatures are lower therefore the materials of the modules suffer less.

This project has sought primarily, to investigate new methods to increase solar energy efficiency, because like as mentioned, now is so low, that in many occasions it is not cost-effective implementation.

With the data obtained leads to the conclusion, already known the experts, that temperature in PV cells plays an important role at the expense of their efficiency. For this reason I believe it is essential find new approaches to enhance its effectiveness, and thus the consumption of such energy, clean, respectful and friendly environment. If we succeed, the future generations will thank us.

ANNEX 2: GFORTRAN PROGRAMS

1) Without refrigeration

2) With refrigeration

1) WITHOUT REFRIGERATION

```
program  without refrigeration

      implicit none
      integer i,j,k,niter,nitermax,is(3),isis,its
      double precision Ts(3),Tc(3),Ta,step,Qsc,Qca,Usc,hsc,hrsc,hrca,hw
      double precision Uca,Nuss,z1,z2,Ra,ni,err
      double precision ni0,dea,Tmsc,Pr,gr,sigm,epsp,epsc,A,check,fu1(3)
      double precision Tc_fi
      integer i_h
      double precision Tp,Qsp,Usp,taoalf
      double precision ganma,Tref,V0,B,IM,VM,Pe
      double precision G,G0,G2,I0
      double precision Upa,Qpa
      double precision fu2(3),Ts_fin


c---------------------------------------------------------------
c     ( calculated Tc assuming
c     Ts is then derived from equations and subsequent
c     reset in the main do loop counter is)
c---------------------------------------------------------------
c
c
c     (Initial values and parameters known)
c


  write(6,*)"initiation"
```

```
      Ta=293.15
      Ts(1)=300.
      Ts(2)=330.
      gr=9.81d0
      dea=3.0d-2
      ni0=1.55d-5
      Pr=7.2d-1
      sigm=5.6704d-8
      epsp=.95
      epsc=.88
      A=1.3
      pi=2*asin(1.)

c
c   (Main loop system)
c
   do isis=1,50

c
c   ( Secant method with dependent variable Ts)
c

   do its=1,2

      Tc(1)=Ts(its)-10.0
      Tc(2)=Ts(its)-1.0d-1
      nitermax=10000
```

```
do i=1,2

        Tmsc=(Ts(its)+Tc(its))/2.
        ni=ni0*((Tmsc/288.)**2.5)*((288.+110.)/((Tmsc)+110.))
        Ra=(2.*gr*(Ts(its)-Tc(i))*dea**3*Pr)/(ni**2.*(Ts(its)+Tc(i)))
        z2=((Ra/5830.)**(1./3.))-1.
        z1=1.-(1708./Ra)
        Nuss=1.+1.44*((abs(z1)+z1)/2.)+((abs(z2)+z2)/2.)
        hsc=(0.027/0.03)*Nuss
        hrsc=(sigm*(Ts(its)**2+Tc(i)**2)*(Ts(its)+Tc(i)))/
     >  ((1./epsp)+(1./epsc)-1.)
        Usc=hsc+hrsc
        hrca=epsc*sigm*((Tc(i)**2+293.15**2)*(Tc(i)+293.15))
        hw=9.5
        Uca=hrca+hw
        Qsc=A*Usc*(Ts(its)-Tc(i))
        Qca=A*Uca*(Tc(i)-Ta)
        fu1(i)=Qsc-Qca

end do

    write(6,*) fu1(1),fu1(2)

c
c   (Iterations for the calculation of Tc. Secant method)
c
```

```
do niter =1,nitermax

    Tc(3)=Tc(1) + fu1(1)/(fu1(2)-fu1(1)) * (Tc(1) - Tc(2))
    if(Tc(3).le.Tc(1)) then
      Tc(2)=Tc(1)
      fu1(2)=fu1(1)
      Tc(1)=Tc(3)
      i=1
    elseif(Tc(3).le.Tc(2)) then
      Tc(1)=Tc(3)
      i=1
    else
      Tc(1)=Tc(2)
      fu1(1)=fu1(2)
      Tc(2)=Tc(3)
      i=2
    end if

    Tmsc=(Ts(its)+Tc(i))/2.
    ni=ni0*((Tmsc/288.)**2.5)*((288.+110.)/((Tmsc)+110.))
    Ra=(2*gr*(Ts(its)-Tc(i))*dea**3*Pr)/(ni**2*(Ts(its)+Tc(i)))
    z2=((Ra/5830.)**(1./3.))-1.
    z1=1.-(1708./Ra)
    Nuss=1.+1.44*((abs(z1)+z1)/2.)+((abs(z2)+z2)/2.)
    hsc=(0.027/0.03)*Nuss
    hrsc=(sigm*(Ts(its)**2+Tc(i)**2)*(Ts(its)+Tc(i)))/
    >   ((1./epsp)+(1./epsc)-1.)
    Usc=hsc+hrsc
```

```
            hrca=epsc*sigm*((Tc(i)**2+293.15**2)*(Tc(i)+293.15))
            hw=9.5
            Uca=hrca+hw
            Qsc=A*Usc*(Ts(its)-Tc(i))
            Qca=A*Uca*(Tc(i)-Ta)

            fu1(i)=Qsc-Qca
            check=abs(fu1(i))
            if(check.le.1.0d-5) go to 1000

 end do

1000    continue

      write(6,*) "result for the iteration Ts,Tc and fu1:",niter,
          >             Ts(its),Tc(i),fu1(i)

      Tc_fin=Tc(i)



      write(6,*) "result for Tc and fu1:",Tc_fin,fu1(i)
      write(6,*) "---------------------------------------"

c
c
c     (Calculation of Tp from the second equation)
c
c
```

```
c
c     (Set up the value of G: we can change the value of G here)
c
c

          i_h=6
          G=100.0d0
          float(i_h)*100.0d0

c
c     (Other parameters)
c

          taoalf=0.8
          I0=4.9
          G0=1.0d3
          ganma=0.0005
          Tref=298.15
          V0=36.8
          B=-0.005
          Usp=200.
          Upa=6.
          G2=taoalf*G
          IM=I0*(G2/G0)*(1+ganma*(Tc_fin-Tref))
          VM=V0*(1+B*(Tc_fin-Tref))
          Pe=IM*VM
          Qsp=(A*G2)-Qsc-Pe
          Tp=-(Qsp/(Usp*A))+Ts(its)
```

```
c
c     (Calculation of Qsp and calculation of the error in the calculation of Qpa)
c


          Qpa=A*Upa*(Tp-Ta)
          err=Qsp-Qpa
          fu2(its)=err




c
c     (last do loop to the two values of Ts)
c


 end do


          check=abs(err)
          if(check.le.1.0d-8) then
          Ts_fin=Ts(its)
          go to 2000
          else
          Ts(3)=Ts(1) + fu2(1)/(fu2(2)-fu2(1)) * (Ts(1) - Ts(2))
          write(6,*) "Ts(1),Ts(2),Ts(3),Qsp-Qpa(per Ts(1),Qsp-Qpa(perT
          >s(2)"
          write(6,*) Ts(1),Ts(2),Ts(3),fu2(1),fu2(2)
          if(Ts(3).le.Ts(1)) then
```

```
          Ts(2)=Ts(1)
          fu2(2)=fu2(1)
          Ts(1)=Ts(3)
        else if(Tc(3).le.Tc(2)) then
         Ts(1)=Ts(3)
        else
          Ts(1)=Ts(2)
          fu2(1)=fu2(2)
          Ts(2)=Ts(3)
        end if

        end if

        write(6,*)"End iteration Ts",isis
        write(6,*)"=========================================="
        write(6,*)

 end do

2000  continue

        write(6,*)
        write(6,*)"results: Tc, Ts, Tp, G "
        write(6,*) Tc_fin,Ts(3),Tp,G

 stop
 end
```

2) WITH REFRIGERATION

```
program  with refrigeration

      implicit none
      integer i,j,k,niter,nitermax,is(3),isis,its
      double precision Ts(3),Tc(3),Ta,step,Qsc,Qca,Usc,hsc,hrsc,hrca,hw
      double precision Uca,Nuss,z1,z2,Ra,ni,err
      double precision ni0,dea,Tmsc,Pr,gr,sigm,epsp,epsc,A,check,fu1(3)
      double precision Tc_fi
      integer i_h
      double precision Tp,Qsp,Usp,taoalf
      double precision ganma,Tref,V0,B,IM,VM,Pe
      double precision G,G0,G2,I0
      double precision F1,Upa,Qpa,Tfm,F,m
      double precision l_abs,d_abs,W,D,pi,hfi,term2
      double precision Di,Ph2o,Qpf,Tf0,Tfi
      double precision G_h2o,C_h2o
      double precision fu2(3),Ts_fin



c-----------------------------------------------------------------
c     ( calculated Tc assuming
c     Ts is then derived from equations and subsequent
c     reset in the main do loop counter is)
c-----------------------------------------------------------------
c
c
c     (Initial values and parameters known)
c
```

```
  write(6,*)"initiation"

        Ta=293.15
        Ts(1)=300.
        Ts(2)=330.
        gr=9.81d0
        dea=3.0d-2
        ni0=1.55d-5
        Pr=7.2d-1
        sigm=5.6704d-8
        epsp=.95
        epsc=.88
        A=1.3
        pi=2*asin(1.)

c
c   (Main loop system)
c
    do isis=1,50

c
c   ( Secant method with dependent variable Ts)
c

    do its=1,2
```

```
      Tc(1)=Ts(its)-10.0
      Tc(2)=Ts(its)-1.0d-1
      nitermax=10000

do i=1,2

      Tmsc=(Ts(its)+Tc(its))/2.
      ni=ni0*((Tmsc/288.)**2.5)*((288.+110.)/((Tmsc)+110.))
      Ra=(2.*gr*(Ts(its)-Tc(i))*dea**3*Pr)/(ni**2.*(Ts(its)+Tc(i)))
      z2=((Ra/5830.)**(1./3.))-1.
      z1=1.-(1708./Ra)
      Nuss=1.+1.44*((abs(z1)+z1)/2.)+((abs(z2)+z2)/2.)
      hsc=(0.027/0.03)*Nuss
      hrsc=(sigm*(Ts(its)**2+Tc(i)**2)*(Ts(its)+Tc(i)))/
     >   ((1./epsp)+(1./epsc)-1.)
      Usc=hsc+hrsc
      hrca=epsc*sigm*((Tc(i)**2+293.15**2)*(Tc(i)+293.15))
      hw=9.5
      Uca=hrca+hw
      Qsc=A*Usc*(Ts(its)-Tc(i))
      Qca=A*Uca*(Tc(i)-Ta)
      fu1(i)=Qsc-Qca

end do

    write(6,*) fu1(1),fu1(2)

c
```

```
c     (Iterations for the calculation of Tc. Secant method)
c

      do niter =1,nitermax

        Tc(3)=Tc(1) + fu1(1)/(fu1(2)-fu1(1)) * (Tc(1) - Tc(2))
        if(Tc(3).le.Tc(1)) then
          Tc(2)=Tc(1)
          fu1(2)=fu1(1)
          Tc(1)=Tc(3)
          i=1
        elseif(Tc(3).le.Tc(2)) then
          Tc(1)=Tc(3)
          i=1
        else
          Tc(1)=Tc(2)
          fu1(1)=fu1(2)
          Tc(2)=Tc(3)
          i=2
        end if

        Tmsc=(Ts(its)+Tc(i))/2.
        ni=ni0*((Tmsc/288.)**2.5)*((288.+110.)/((Tmsc)+110.))
        Ra=(2*gr*(Ts(its)-Tc(i))*dea**3*Pr)/(ni**2*(Ts(its)+Tc(i)))
        z2=((Ra/5830.)**(1./3.))-1.
        z1=1.-(1708./Ra)
        Nuss=1.+1.44*((abs(z1)+z1)/2.)+((abs(z2)+z2)/2.)
        hsc=(0.027/0.03)*Nuss
```

```
      hrsc=(sigm*(Ts(its)**2+Tc(i)**2)*(Ts(its)+Tc(i)))/
     >   ((1./epsp)+(1./epsc)-1.)
      Usc=hsc+hrsc
      hrca=epsc*sigm*((Tc(i)**2+293.15**2)*(Tc(i)+293.15))
      hw=9.5
      Uca=hrca+hw
      Qsc=A*Usc*(Ts(its)-Tc(i))
      Qca=A*Uca*(Tc(i)-Ta)

      fu1(i)=Qsc-Qca
      check=abs(fu1(i))
      if(check.le.1.0d-5) go to 1000

 end do

1000   continue

     write(6,*) "result for the iteration Ts,Tc and fu1:",niter,
     >            Ts(its),Tc(i),fu1(i)

     Tc_fin=Tc(i)


     write(6,*) "result for Tc and fu1:",Tc_fin,fu1(i)
     write(6,*) "-------------------------------------"

c
c
```

```
c     (Calculation of Tp from the second equation)
c
c
c
c     (Set up the value of G: we can change the value of G here)
c
c

          i_h=6
          G=100.0d0
          float(i_h)*100.0d0

c
c     (Other parameters)
c

          taoalf=0.8
          I0=4.9
          G0=1.0d3
          ganma=0.0005
          Tref=298.15
          V0=36.8
          B=-0.005
          Usp=200.
          l_abs=204.d0
          d_abs=3.d-3
          Di=3.d-3
          D=Di+2*d_abs
```

```
      W=.8/11.
      hfi=1500.
      Tfi=298.15
      G2=taoalf*G
      IM=I0*(G2/G0)*(1+ganma*(Tc_fin-Tref))
      VM=V0*(1+B*(Tc_fin-Tref))
      Pe=IM*VM
      Qsp=(A*G2)-Qsc-Pe
      Tp=-(Qsp/(Usp*A))+Ts(its)
      write(6,*) "G",G
      write(6,*) "Qsp",Qsp
      write(6,*) "Tp",Tp
c
c     (Set up the values of Ta, mass flow rate (G_h2o)
c     and other parameters)
c
      Upa=6.
      Ta=293.15
      G_h2o=0.01
      C_h2o=4186.
      Qpa=A*Upa*(Tp-Ta)
c
c     (Calculate F1 with F and Upa:
c      m -> F -> F1)
c
```

```
      m=(Upa/(l_abs*d_abs))**.5
      F=dtanh((m*(W-D)/2.))/(m*(W-D)/2.)
      term2=1./(Upa*(D+(W-D)*F))+(1./(pi*Di*hfi))
      F1=1./(W*Upa)*(1./term2)

c
c   (calculation of Qpf from 3th equation
c    (Qsp-Qpa-Qpf=0))
c

      Qpf=Qsp-Qpa
      write(6,*)"Qpf",Qpf

c
c   (Calculation of Tf0 from Qpf expression)
c

      Tfm=Ta+((A*F1*Qsp-Qpf)/(A*F1*Upa))
      if (Tfm.gt.Tp) Tfm=Tp
      Tf0=2*Tfm-Tfi

c
c    (Calculation of Ph2o and calculation of the error
c    in the calculation of Qpf)
```

```
c
          Ph2o=G_h2o*C_h2o*(Tf0-Tfi)
          write(6,*)"Ph2o",Ph2o
          err=Ph2o-Qpf
          write(6,*)"err",err
          fu2(its)=err
          write(26,*) "Tfm,Tf0,Ph2o,Qpf",Tfm,Tf0,Ph2o,Qpf

c
c    (In the end do loop for two values of ts)
c

  end do

          check=abs(err)
          if(check.le.1.0d-5) then
            Ts_fin=Ts(its)
            go to 2000
          else
            Ts(3)=Ts(1)
            fu2(1)/(fu2(2)-fu2(1)) * (Ts(1) - Ts(2))
            write(6,*) Ts(1),Ts(2),Ts(3),fu2(1),fu2(2)
          if(Ts(3).le.Ts(1)) then
            Ts(2)=Ts(1)
            fu2(2)=fu2(1)
            Ts(1)=Ts(3)
          elseif(Tc(3).le.Tc(2)) then
            Ts(1)=Ts(3)
```

```
            else
              Ts(1)=Ts(2)
              fu2(1)=fu2(2)
              Ts(2)=Ts(3)
            end if
           end if

 end do

2000  continue

           write(6,*)
           write(6,*)"results: Tc, Ts, Tp, G "
           write(6,*) Tc_fin,Ts_fin,Tp,G,Tf0

      stop
      end
```

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